REMBASS
DATA TRANSMISSION SUBSYSTEM
DECISION RISK ANALYSIS (DRA)

PROJECT MANAGER

REMBASS

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PROJECT MANAGER
REMOTELY MONITORED BATTLEFIELD SENSOR SYSTEM
FORT MONMOUTH, NEW JERSEY

Remotely Monitored Battlefield Sensor System
(REMBASS)

Data Transmission Subsystem

Decision Risk Analysis (DRA)

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This REMBASS Data Transmission DRA is the result of the efforts of many individuals over a period of several months. The Data Transmission Subsystem Team was responsible for the largest part of the project, but the information provided by special consultants proved invaluable.

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SECTION I

CONCLUSIONS AND RECOMMENDATIONS OF THE DTS ENGINEERING ANALYSIS

1.0 ENGINEERING ANALYSIS 1. TRANSMISSION TECHNIQUES

1.1 Conclusions. The narrowband technique, using a Frequency Division Multiplex (FDM) system, was shown to be clearly superior to wideband when all criteria are properly weighted and averaged. In the area of Electronic Countermeasures (ECM) the wideband technique is preferred except against broadband jammers. However, it was recognized that no transmission technique is completely and forever immune to a dedicated enemy jamming threat. Therefore, the advantages of a wideband technique in this area did not outweigh its disadvantages in other areas considered.

The results of the evaluation were subjected to a sensitivity analysis to determine the effects of possible incorrect weighting factors or inconclusive ratings against the criteria. The Narrowband FDM Transmission Technique remained the better choice.

1.2 Recommendation. A channelized narrowband transmission technique (FDM) is recommended. The DTS design should be such that a conversion from the FDM to a narrowband frequency hopping system can be made in the future if the development of this technique materializes to a cost-effective capability. Converting the FDM to narrowband frequency hopping would provide a measure of protection against jamming not available with FDM.

2.0 ENGINEERING ANALYSIS 2. REPEATER TYPES

2.1 Conclusion. An all digital repeater design was found as ranking slightly above a combined digital/analog design. If the requirement for analog data transmission is eliminated, the decision as to the repeater type will have been made regardless of the analysis.

2.2 Recommendation. It is recommended that digital only repeater types be designed, with the decision that the digital/analog combined design be based on the requirement to transmit analog data.

3.0 ENGINEERING ANALYSIS 3. REPEATER CONFIGURATION

3.1 Conclusion. Of the alternatives considered, the one which uses a single configuration with common electronics received the highest ranking by a reasonable margin. All weighting techniques used in the analysis showed similar results. Likewise, a sensitivity analysis with variable weights did not change the ranking of this alternative versus the other alternatives. However, in reviewing the weights which were assigned to the various criteria and subcriteria, the team believes that a disproportionate weight was given to some criteria which tended to favor this alternative over the others. In particular, human factors are believed to be of much greater importance than versatility. Similarly, reliability is given a significantly greater weight in this engineering analysis than others. In view of this, the team does not believe the analysis is conclusive.

3.2 Recommendation. Based on the above statements, the team recommends that a separate configuration with common electronics be used for designing repeaters for air delivered and hand emplaced use (Alternative B).

4.0 ENGINEERING ANALYSIS 4. EQUIPMENT CONSTRUCTION METHODS

4.1 Conclusion. A common functional modular design ranks significantly higher than a unique design of each hardware element (repeaters, sensors, etc.). The alternative which incorporates common LSI chips as sub-functional units along with common functional modules ranked a very close second. Although the results of the sensitivity analysis did not change the relative ranking of alternatives, it was concluded by the team that the difference in ranking of alternatives A and B was not significant.

4.2 Recommendation. In view of the close ranking between alternatives A and B, the team recommends that a common functional modular design be utilized for the hardware elements of the DTS and in addition, consider using sub-functional units which may have been developed by the Government at the time of contracting for the DTS hardware design. Typical sub-functional units which are being funded in development are the digital synthesizer and reference oscillator (TCVCXO).

5.0 ENGINEERING ANALYSIS 5. SENSOR CONTROL MODULE

5.1 Conclusions. The relative ranking of the two alternatives, based on the weighted and sensitivity analyses, was not conclusive. This could be due to several factors: a) the alternatives are equally capable of providing the operational requirements; b) the weighting factors applied to the criteria are questionable; or c) the set of evaluation criteria is not sufficient or complete.

5.2 Recommendation. Based on the inconclusive results of the evaluation, no recommendation is made. If the possible use of an SCM with mini-sensors is still considered a viable alternative, additional evaluation with other criteria should be considered.

6.0 ENGINEERING ANALYSIS 6. NUMBER OF CHANNELS FOR REPEATER

6.1 Conclusions. Of the three alternatives considered, single channel repeaters received the highest ranking in all four weighting techniques used in the analysis. The alternative of providing both single and dual channel repeaters for REMBASS use ranked second in all weighting techniques, with the combined single/dual channel repeater design always last.

Again, in reviewing the relative weights which were assigned to the various criteria, it was the conclusion of the team members that some of the weight assignments of the subcriteria were not realistic. For example, the subcriteria of cost which were improperly weighted were: a) acquisition costs; and b) life cycle support costs. Since the sensitivity analysis only considered the results of a perturbation of the major criteria (e.g., cost), these anomalies would not show up in the analysis. Restructuring the subcriteria weights would not necessarily reverse the difference between the first and second ranked alternatives. Whether the approximate 10% differential is significant for choosing an alternative has not been determined.

6.2 Recommendation. It is recommended that single channel repeaters be developed for REMBASS. In view of the factors discussed above, it is possible that dual channel repeaters may be cost effective in some applications. Therefore, it is also recommended that development of dual channel repeaters as well as single channel repeaters be considered.

7.0 ENGINEERING ANALYSIS 7. MODULATION TECHNIQUES

7.1 Conclusions. The analysis indicates that Phase Shift Keying (PSK) is the best method of digital data modulation of all the methods considered. In order for PSK to perform better than other methods, a coherent or matched filter receiver must be used. Under certain conditions a coherent system may be approximated, given sufficient time for phase and frequency synchronization at the receiver. Likewise, a matched filter processor may be accomplished for burst type digital signals using a Surface Wave Device (SWD). Unfortunately, SWD's are only applicable to wideband type signals. Since the analysis was made, independent of the type of transmission techniques (wideband or narrowband), and since a narrowband technique was recommended as a result of Engineering Analysis 1, the results of this engineering analysis must be evaluated in light of the narrowband transmission technique. Consequently, PSK tends to lose its ranking with a narrowband system such as REMBASS will use. Similar conclusions are applicable to other methods which require a coherent processor or matched filter receiver. These are a) Differential PSK; and b) Chirp.

On-off Keying (OOK) is ranked rather high, if one is able to insure a specified minimum $(S/N)_{min}$ at the receiver, which is determined by the required message bit error rate. If this $(S/N)_{min}$ cannot be insured, the performance of the system degrades drastically.

Since the REMBASS DTS cannot be insured of a given receiver (S/N), using OOK modulation is not considered to be advisable. Adaptive threshold techniques may be incorporated in the receiver in some cases but this would impact on message structure and message duration. It is believed that sufficient weight was not given to error performance in the analysis and too much weight was given to spectrum utilization. Changing these weights would easily reverse the ranking of OOK vice BFM or BFSK.

Recommendation. Binary FM and Binary FSK differ in the receiver more than in the transmitter. In fact, a BFM receiver can receive a BFSK modulated signal. A BFM receiver is used if both analog and digital data are transmitted. If only digital data is transmitted a BFSK dual filter receiver will degrade more gracefully with decreasing (S/N) than BFM; therefore, since it appears that REMBASS will not transmit analog data, a BFSK modulation of digital data is recommended.

8.0 ENGINEERING ANALYSIS 8. MESSAGE TYPES

8.1 Conclusion. The analysis indicates that if both digital and analog data are to be transmitted in REMBASS, analog data should not be digitized before transmission but should be used directly as a modulating signal.

8.2 Recommendation. If both analog and digital data are to be transmitted, analog data should be used directly to modulate the carrier; whereas, the digital data would use dual frequency modulation for the two binary states of the digital data.

9.0 ENGINEERING ANALYSIS 9. FREQUENCY CHANGING METHODS

9.1 Conclusion. The analysis indicated that three methods of frequency changing should be used in the REMBASS DTS equipment as applicable: a) digital frequency synthesizer; b) single frequency oscillator module; and c) crystal substitution. The former is the more expensive and would be used only in those equipments in which the versatility of frequency selection was an overriding consideration. The second method would be used in equipments when the need for wide environmental capability (temperature) was required; but, frequency changing was seldom required except at a depot level of maintenance. Crystal substitution would be used only if the accuracy and stability requirements of the equipment was not severe. If $\pm$ 5 ppm frequency stability was required, even at limited temperature ranges, it is not expected that this method would be usable.

9.2 Recommendation. The methods indicated in the analysis, and discussed above, are recommended.

10.0 ENGINEERING ANALYSIS 10. MESSAGE CODING

10.1 Conclusions. The analysis indicates that a single bit parity check error detection coding for REMBASS digital data messages is preferred over single error correction coding, or no coding. It is emphasized that this assumes that the DTS data messages contain no classified information. That is, reliability of data communication is the primary concern.

The DTS team does not agree with the relative weights applied to the cost subcriteria; however, this would not change the results since the rating of the two top alternatives are equal for these subcriteria.

10.2 Recommendation. It is recommended that a single bit parity check be incorporated with all digital data for error detection only.

11.0 ENGINEERING ANALYSIS 11. REPEATER OPERATIONAL TESTING

11.1 Conclusion. Command testing of operational repeaters ranked first in all four weighting techniques used in the analysis. The evaluation was predicated upon a command link being required for some sensors and therefore, did not consider a command link being included for the sole purpose of testing repeaters. If a command link is not available, the results of the analysis would have to be reviewed for the possibility of a differenct conclusion.

11.2 Recommendation. It is recommended that repeaters include the capability for some degree of operational testing via the sensor command link.

TABLE I - I

SYMBOL DEFINITIONS

SYMBOL	DEFINITION
α (r)	Net sensor-to-receiver losses
(A) (r)	Channel Attenuation (excluding fading) characteristics
β (r)	Net jammer-to-receiver losses
B	System bandwidth
B_c	Channel bandwidth
B_D	Data bit-rate bandwidth
B_F	FFH bandwidth per channel
B_I	Information bandwidth
B_J	Bandwidth of jammer noise
B_n	Receiver noise bandwidth
B_N	Sensor data bandwidth
B_P	Pseudo-noise transmission bandwidth
B_R	Bit rate bandwidth
B_{RN}	Maximum narrowband bit-rate bandwidth
B_{RW}	Wideband bit-rate bandwidth
C	Number of channels (narrowband)
c(t)	Carrier
(E_b/n)	Energy per bit/one-sided noise power density
Δf	Frequency uncertainty due to oscillator instabilities,etc.
F	Receiver noise factor (also figure)

SYMBOL	DEFINITIONS
FAB	Data bit false alarm
FAD	expected false alarm per day
f_m	Highest analog frequency
G_{AR}	Receiving antenna gain
G_{AT}	Transmitting antenna gain
G_P	Processing gain
j(t)	Jamming (jammer input) signal
k	Boltzmann's constant
λ	Average rate/sensor
L	Preselector filter losses, etc.
Lp	Propagation loss
m(t)	Message
m'(t)	Demodulated replica of m(t)
N	(PN code bits)
Ni	Effective receiver noise power (total)
n	Number of sensors
η	Noise power density equals 10 log (k Te)
$\eta(t)$	Noise
P	Probability of message overlap
P_c	Probability of false alarm during chip time
P_{DB}	Probability of data bit detection
P_{DCB}	Probability of detection per code bits
P_{DM}	Probability of message detection
P_e	Error probability
P_{FAB}	Probability of data bit false alarm

SYMBOL	DEFINITIONS
P_{FAM}	Probability of message false alarm
P_{FFH}	Probability that a net is in one of the FFH bands
P_J	Total jammer power (noise-like signal)
P_{PNSS}	Probability that a single net is within REMBASS band
Ps	Sensor power
$P_{SFH/FD}$	Joint probability net within band and on REMBASS channel
P_{sw}	Wideband transmitter (sensor power output)
$P_t(t)$	Transmitter output power
R_C	Chip rate
R_D	Data rate
r_i	Maximum range between sensor/relay, relay/relay or relay/receivers
r_j	Minimum range between jammer and any receiver
S/J	Signal-to-jammer power ratio
$(S/N)_{IF}$	Required signal-to-noise ratio into the demodulator
(S/N)q	Signal-to-quantization ratio
$S_t(t)$	Radiated signal
$S_R(t)$	Signal at receiver input terminals
T_A	Antenna noise tempeaature
T_B	Bit duration
T_e	Effective receiver noise temperature or equivalent noise temperature
T_m	Message duration (length)
Ts	Specified time interval
T_{SB}	Sub-bit duration
τ	Chip duration

SECTION II

ENGINEERING ANALYSIS 1 - TRANSMISSION TECHNIQUES

1.0 SUMMARY

This analysis addresses the transmission technique that will be used in the REMBASS Data Transmission Subsystem. The alternatives were evaluated against a specific set of criteria: cost; performance; versatility; schedule; technical risk; and logistics. The analysis concluded that channelized narrowband transmission (FDM) should be utilized. This technique should be implemented in such a way so as to facilitate conversion to a frequency hopping technique at a later date.

2.0 INTRODUCTION

The REMBASS system is composed of several major subsystems. Several different alternative subsystem designs may be found which meet the system operational and functional requirements of REMBASS within certain constraints. In order to determine which subsystem alternative provides the best choice, alternatives are evaluated and analyzed against common criteria and one or more possible alternatives are selected as candidates for final system components. This report is concerned with the selection of a transmission technique for the Data Transmission Subsystem (DTS).

3.0 STATEMENT OF THE PROBLEM

Data from REMBASS must be communicated to remote readout stations via radio frequency (RF) links, especially designed for this purpose. In some cases the link will include one or more radio repeaters due to the distance between sensor and readout. This RF communication link must perform reliably in an environment which consists of other RF emitters, extraneous noise sources, and possible enemy jamming. Within given constraints, a communication technique must be selected which provides the required operation capability and is the optimum alternative measured against the given criteria.

4.0 ALTERNATIVES

Two alternative transmission techniques will be evaluated and analyzed to determine which technique most nearly satisfies the REMBASS requirements. These are a) narrowband; and b) wideband.

4.1 Narrowband. A narrowband transmission system is characterized by the ratio of information bandwidth to baseband data bandwidth being a factor of about 10. Therefore, the system bandwidth may be divided into many narrowband channels. Each channel may be shared by many transmitter/receivers, all operating on the same carrier frequency. Two types of narrowband systems will be evaluated. These are a) Slow Frequency Hop (SFH); and b) Channelized Frequency Division (FD).

4.1.1 SFH System. The SFH system is similar to the channelized FD in that many narrowband channels are created from the available system bandwidth. In operation, a transmitter and receiver will systematically switch from one channel to another in some pseudo-synchronous predetermined manner, only remaining on a given channel for a short period of time before switching to the next channel. It is not mandatory that a transmission occur before switching to a different channel. The switching period should be long compared to a message duration; however, it should not be so long that many sensor messages are transmitted during each period. Otherwise, the message loss may be inordinately large. Optimizing the switching period versus the number of sensors on a channel and relative clock stabilities will be a major concern with this technique.

4.1.2 Channelized FD System. The Channelized FD System is very simple and straightforward. The system bandwidth is divided into many narrowband channels and a given number of sensors are assigned to a fixed channel. The channel width is determined by message rate, modulation methods, co-channel isolation requirements, etc. The South East Asia Operational Sensor System (SEAOPSS) is representative of this technique.

4.2 Wideband. A wideband transmission system is characterized by a large ratio of information bandwidth to data rate bandwidth. The objective of these type systems is usually that of trading bandwidth for processing gain, or signal-to-noise ratio. Two types of wideband systems will be evaluated: a) Pseudo-noise Spread Spectrum (PNSS); and b) Fast Frequency Hop (FFH). Both of these types have attributes which are desirable for certain applications.

4.2.1 PNSS. This is a wideband system in which the energy in the data signals is spread over a wide frequency band by a coding operation prior to modulation and transmission. To provide a continuous transmission spectrum, as well as provide some degree of countermeasure, the transmittal data is made to look like noise by coding with a PN code. If a coherent system can be designed, significant processing gain may be obtained; however, this is usually at the expense of high peak power.

4.2.2 FFH. This is a wideband system technique which is also a spread spectrum subsystem in which some of the bandwidth spreading is obtained by progressively shifting the center frequency of transmission around within the system band. The bandwidth of a given transmission is inversely proportional to the number of hopping frequencies used. Synchronization of the hopping rate of receiver and transmitter is a must for proper operation of a FFH system and this feature tends to limit the usefulness of the FFH wideband technique.

5.0 CRITERIA

The criteria which will be used in the comparative evaluation of alternatives axxociated with this engineering analysis are defined below. In 6.0, each alternative is evaluated against this criteria. All alternatives will be ranked against other alternatives for each criterion. Then, each subcriterion will have a summary evaluation sheet from which the relative ranking of the alternatives can be determined for that particular criterion. Finally, a relative ranking will be compiled for each major criterion.

This data will be used in 7.0 to make a comparative analysis of the alternatives to determine which most nearly meets the REMBASS requirements. In cases where the relative weight of an alternative within a given criterion is not considered exact, a sensitivity analysis (see 8.0), will be performed to determine the effects of errors in ratings.

5.1 Performance Parameters

5.1.1 Processing Gain. This is a measure of efficiency of signal processing in the receiver. It is usually measured in terms of the signal-to-noise ratio at the output of the processor and the carrier-to-noise ratio at the receiver IF (or limiter) output.

5.1.2 Required Signal-to-Noise Ratio (S/N). This is the ratio required to meet the operational requirements of data error rates or analog signal quality.

5.1.3 Error Probabilities. This is a statistical parameter which relates the expected errors in a given quantity of digital data as a function of some other parameter such as (S/N).

5.1.4 Transmitter Power. This parameter is used to specify the power required from a transmitter to meet such operational requirements as error rates, transmission range, etc., for different types of transmission and modulation techniques.

5.1.5 ECM/RFI. Electronic countermeasures (ECM) and radio frequency interference (RFI) are two forms of electronic RF signals which a communication system must be protected against to the maximum extent practicable.

5.1.6 Spectrum Utilization. This is a measure of the efficiency with which a given transmission and modulation technique are able to utilize a given assigned RF spectrum. For REMBASS it is measured in terms of the number of separate communication channels, or the number of sensors, which may be accommodated within the band.

5.2 Versatility. Versatility implies the ability to accommodate to different situations. In the case of the DTS, it means the ability of the transmission system to communicate analog as well as digital data. It also is used to indicate the modifications or compromises in design necessary to provide this capability for a given transmission technique.

5.3 Reliability. This is another statistical term which is used to indicate quality of performance. It is generally defined as the probability that the device will perform its function without failure for the period of time intended under the specified environmental conditions.

5.4 Schedule

5.4.1 Development Time. This is the time required to perform any necessary engineering development on a system design before preproduction models are available.

5.5 Risk

5.5.1 Development Risk. This criterion is a qualitative means of estimating the probability that a chosen technique, design, approach, etc., will result in a successful conclusion. It is a non-deterministic parameter in that it depends on the judgement of the evaluator as well as the capability of undetermined contractors.

5.6 Logistics

5.6.1 Test Equipment Required. This is the special test equipment required to support a given alternative at any echelon of maintenance and repair.

5.6.2 Maintenance Skills Required. These are special skills which are required due to the unique characteristics of the alternative.

5.6.3 Equipment Adjustments Required. This criterion is the measure of time and expense of putting the equipment in good operating condition; also, the number and frequency of adjustments necessary to keep it in operation.

5.7 Costs

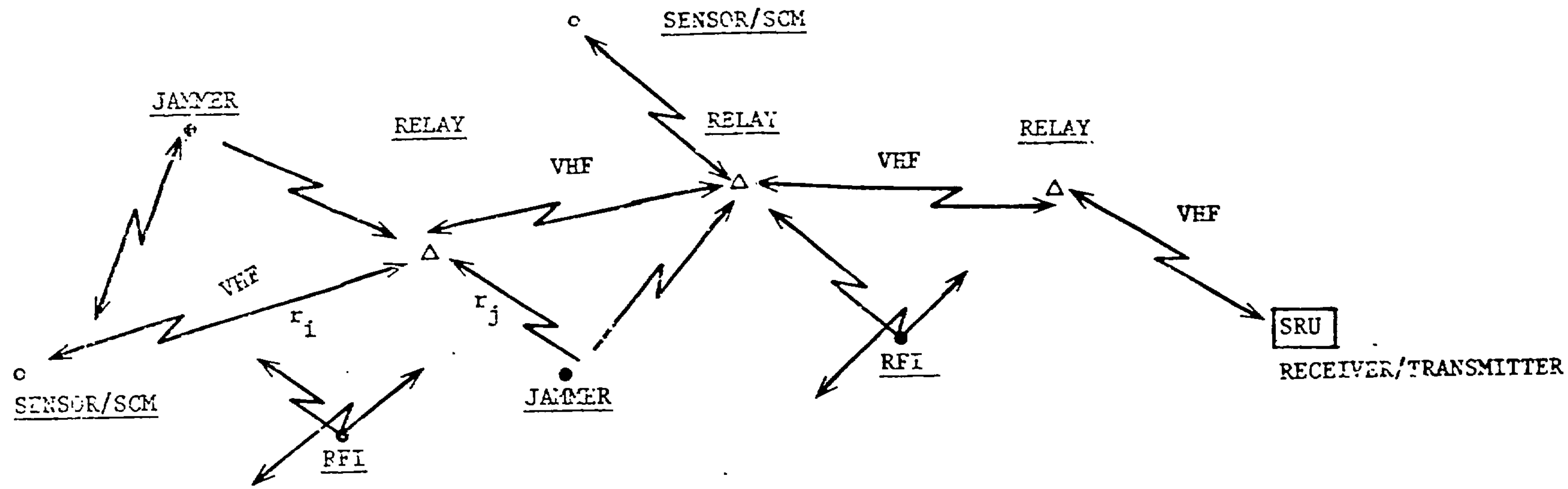
5.7.1 R&D Costs. These costs are associated with, and are directly related to, the development time criterion.

5.7.2 Acquisition Costs. This cost item includes recurring and non-recurring investment costs to provide the initial equipment, components, software, etc., for the complement of Army users of the system. R&D costs are sometimes included in acquisition costs but are broken out separately here.

5.7.3 Life Cycle Support Costs. These are "operating costs" as defined in AR37-18. Included are a) personnel (crew and maintenance); b) consumption (equipments); c) Integrated Logistic Support (ILS); d) transportation; and c) depot maintenance.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 General. The REMBASS DTS is required to provide a reliable method of getting data from remote sensors to a receiver at a Sensor Readout Unit (SRU) and also to provide a command link from the SRU to certain commandable sensors. This must be accomplished within an environment of other locally radiated signals (RFI), possible intentional jamming by unfriendly sources, and other indigenous noise signals. A single thread link is shown in Figure 2-1 where three repeaters are cascaded between the sensor field and the SRU. This is the maximum number of repeaters which is expected to be used on a channel. Typically one, or possible two repeaters will satisfy most requirements.



r_i = Maximum range between sensor/relay, relay/relay, or relay/receivers

r_j = Minimum range between jammer and any receiver

Figure 2-1

SINGLE THREAD REMBASS DTS WITH INTERFERING SOURCES

Where possible, results of other engineering analyses on similar systems have been evaluated for possible incorporation in this report. 1/

6.2 ECM Threat (Classified). See Addendum A to this engineering analysis.

6.3 RFI Environment (Classified). See Addendum A to this engineering analysis.

6.4 Requirements and System Parameters. For the purpose of this evaluation, the following system performance requirements and parameters will be used:

a)	Probability of Message Error (Total)	4×10^{-3}
b)	False Alarm Rate	1/day max.
c)	Missed Message Probability	2% max
d)	Maximum Active Sensors	(See TOA MPE)
e)	Maximum Number of Repeaters in Tandem	3
f)	Data Requirements (type)	Digital and Analog
g)	Avg. Digital Msg Rate (Assumed)	.005/sec./sensor
h)	Digital Message (Assumed)	40 data bits (including preamble)
i)	Analog Message	10 sec./2kHz Bandwidth
j)	Range:	See Classified Addendum
	1) Sensor (SCM) to RR or UCR (LOS)	
	2) RR to UCR (LOS)	
k)	System Bandwidth	
l)	Sensor Tx Oscillator Instability	$\pm$ 10 ppm
m)	Relay Rx Oscillator Instability	$\pm$ 10 ppm
n)	Relay Tx Oscillator Instability	$\pm$ 10 ppm
o)	UCR Oscillator Instability	$\pm$ 2 ppm

1/ See response to ECOM REQ DAAB07-72-Q-0181

6.5 DTS Model. A signal model of a typical data transmission channel is shown in Figure 2-3 which is representative of any of the transmission techniques to be considered in this analysis. A sensor is assumed to be transmitting to a receiver in the presence of noise, RFI, and jamming. A carrier, c(t), is modulated by a (coded) message signal, m(t), amplified and coupled to the communication channel by the antenna. The radiated signal, $S_t(t)$, suffers free space attenuation, possible fading, and corruption by noise, n(t), and intentional jamming, j(t), before arriving at the receiver terminals. The signal is further corrupted by thermal noise in the receiver. After amplification and filtering, the signal is demodulated and detected to recover a replica, m'(t), of the message input at the sensor modulator. The data link is designed, within specified constraints, to insure that the message output, m'(t), matches the message input m(t), to a specified precision. That is, the probability that the two are different must be some specified maximum value. For digital data messages, this is given as a probability of message error per message sent. The transmission techniques listed as alternatives in 4.0 will be investigated to determine how they compare in meeting the REMBASS requirements, when measured against the criteria listed in 5.0.

The message structure shown in Figure 2-2 will be assumed for comparison purposes.

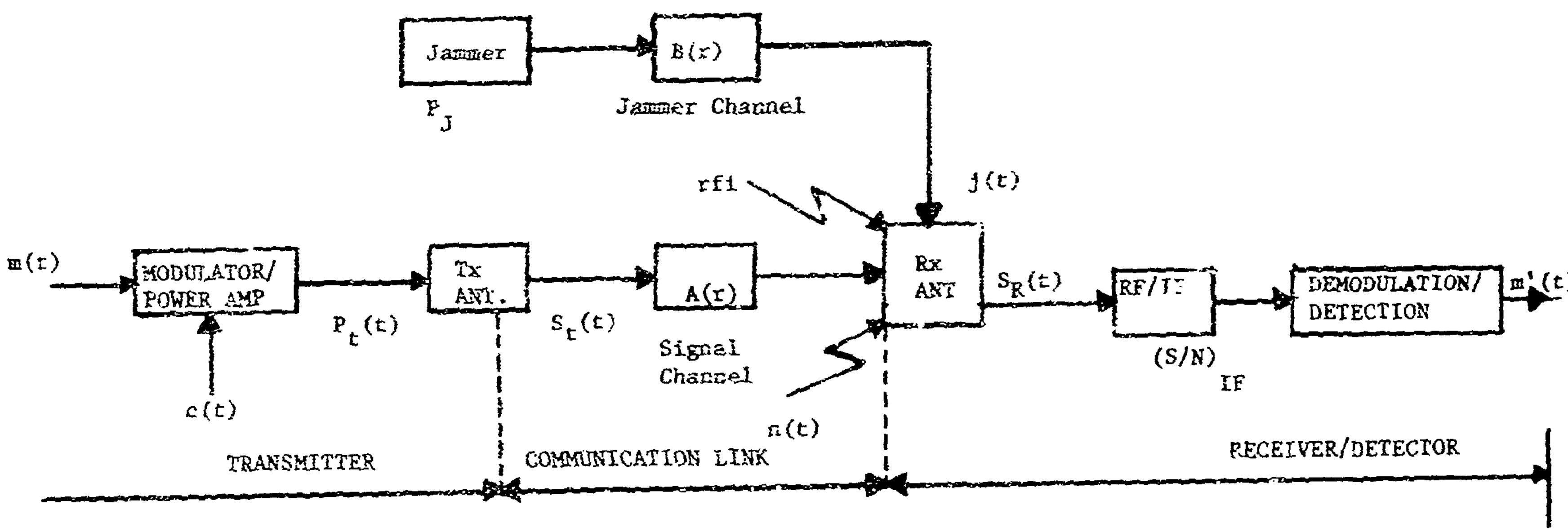
	Start Bit		
X-Bit Preamble	1	Y-Bit ID	Z-Bits (Information/control)

40 Bits Total

Tm = Message Duration (Digital Only)

FIGURE 2-2

ASSUMED REMBASS DIGITAL MESSAGE



$c(t)$ = carrier signal
$m(t)$ = message signal (coded)
$P_t(t)$ = transmitter output power
$S_t(t)$ = radiated signal
$n(t)$ = equivalent thermal noise input
$j(t)$ = jammer input
$A(r)$ = channel attenuation (excluding fading) characteristics
$S_R(t)$ = signal at receiver input terminals
$(S/N)_{IF}$ = required signal-to-noise ratio into the Demodulator/Detector

FIGURE 2-3

GENERALIZED DATA TRANSMISSION CHANNEL

6.6 Data Link Performance Parameters. In the analysis of a data transmission system it is assumed that effects of the separate inputs may be added or superposed. Considering the power balanced for the data signal first, one finds:

1) $10 \log P_S\ (dB_m) \geq 10 \log (S/N)_{IF}\ (dB) + 10 \log \alpha(r)\ (dB)$
$+ 10 \log N_i\ (dBM)$

where

P_S = Sensor transmitter power (m watts)

$(S/N)_{IF}$ = Required signal-to-noise ratio

$\alpha(r)$ = net link losses (antenna gains, path losses, etc.)

N_i = kTe Bn = Effective receiver noise power (total)

] [K = Boltzmann's const.

] [Te = TA + (LF-1) 290°K = Effective receiver noise temperature in degrees Kelvin

] [TA = Receiver Antenna noise temperature

] [L = Preselector filter losses, etc.

] [F = Receiver noise factor

] [B_n = Receiver noise bandwidth

For purposes of comparing wideband and narrowband transmission techniques, it will be assumed initially that the receiver processor is matched to the incoming signal using either a correlation processor with coherent detection or matched filter with sampling. If digital data is being transmitted and processed, the output of the processor is related to the $(S/N)_{IF}$ as follows:

2) $(S/N)_{IF} = \left(\frac{E_b}{\eta}\right)\left(\frac{B_R}{B_I}\right)$

where

$\left(E_b/\eta\right)$ = $\frac{\text{average energy per bit}}{\text{one-sided noise power density}}$; (Required (S/N)o for given bit error rate)

B_R = Bit rate bandwidth

B_I = Information bandwidth of the system

$10 \log \left(\frac{B_I}{B_R}\right)$ = Processing gain in dB.

With the above assumption 1 becomes

$$3)\quad 10 \log Ps \geq 10 \log \left(E_b/\eta\right) dB + 10 \log \left(\frac{B_R}{B_I}\right) dB + 10 \log \alpha(r)\ dB$$

$$+ 10 \log (KTe)\ \frac{dBm}{Hz} + 10 \log (B_n)\ \ dB$$

Given the system requirements on range, error rate, data rate, detection and false alarm probabilities, etc., equation 3 determines the sensor transmitter power required where the only source of interference is Gaussian type noise with uniform power spectral density, η watts-sec.

If a noise jammer is also operating in the sensor band this noise may be much more significant to contend with than the extraneous thermal-type noise; therefore, the sensor signal-to-jammer power ratio is of primary importance. This is given by

$$4)\quad 10 \log (S/J) = 10 \log \left(\frac{P_S}{P_J}\right) \left(\frac{B_J}{B_N}\right) \left(\frac{\beta(r)}{\alpha(r)}\right)$$

P_S = Sensor power output

P_J = Total jammer power (noise-like signal)

B_J = Bandwidth of jammer noise

$\beta(r)$ = Net jammer-to-receiver losses

$\alpha(r)$ = Net sensor-to-receiver losses

B_n = Receiver noise bandwidth

Since $\alpha(r)/\beta(r)$ is independent of the transmission technique it will be assumed unity for comparison purposes and therefore 4 becomes

$$5)\quad 10 \log \left(\frac{S}{J}\right) = 10 \log \left(\frac{P_S}{P_J}\right)\left(\frac{B_J}{B_n}\right) ;\ B_J \geq B_n$$

A measure of comparison between transmission techniques is the power required by the sensor transmitter to provide a given measure of performance. For the ideal systems described above, it is clear from 3 and 5 that P_S is a function of the processing gain and noise bandwidth for each technique, other things being equal. The wideband and narrowband technique will be compared on this basis. They will also be compared by considering the limitations of each in obtaining the ideal performance indicated above.

6.6.1 Wideband Transmission Systems. Wideband transmission systems are generally characterized as having a large transmission bandwidth compared to the baseband data bandwidth. It is also true that the frequency instability of the transmitter carrier (as well as the receiver local oscillator) is generally small compared to the transmission bandwidth.

Therefore, the noise bandwidth, B_{η}, of the receiver may be considered essentially equal to the transmission bandwidth, B_I. Equation 3 may then be put in the following form:

$$6)\quad P_{SW}\ (\text{dBm}) \geq \eta \left(\frac{\text{dBm}}{\text{Hz}}\right) + \left(\frac{E_b}{\eta}\right)\ (\text{dB}) + B_R\ (\text{dBHz}) + \alpha(r) \quad (\text{dB})$$

P_{SW} = Wideband sensor power in dBm = 10 log Psw (mWatt)

η = 10 log (kTe)

This result would indicate that the lowest bit rate B_R possible, consistent with the maximum source message rate requirements, should be used. Two factors preclude the arbitrary selection of B_R: a) multiple users of the band require short message lengths to reduce the self interference probability; and b) analog matched filters cannot, as yet, be fabricated for large bit periods.

6.6.1.1 <u>Message Length</u>. For lack of a better model the sensor transmissions are assumed to be Poisson distributed with an average rate of .005/sec./sensor. If the message duration is Tm, the interval between messages must be greater than 3Tm to allow the messages to be relayed without interference, assuming store-and-forward repeaters on the same channel. The probability of two or more sensors giving a response in an interval 3Tm is approximately (see Addendum B)

$$7)\quad P \simeq 3\lambda\ Tm\ (n-1) \qquad (\text{If } \lambda Tm \ll 1)$$

λ = avg. rate/sensor = .005 msg/sec/sensor

n = Number of sensors

Tm = Message Length

P = Probability of message overlap

The probability of message overlap is determined from the missed message rate requirement. The 2% missed message rate specified must be divided between message overlap loss and probability of non- detection due to noise degradation of the signal. The larger the percentage assigned to overlap, the larger will be the probability of message detection requirement, and therefore the larger the signal-to-noise ratio required for a given false alarm rate. A value of 1% will be assumed for overlap loss. From equation 7, either the maximum message length may be determined, given the number of sensors to be accommodated, or, if T_m is determined from other constraints, the maximum number of sensors which the system may accomodate may be determined.

6.6.1.2 Matched Filter Limitations. For short burst type transmission, which is typical of REMBASS digital data messages, only analog matched filters appear feasible for detection and processing of wideband signals in the receiver. The present state-of-the-art techniques for fabricating analog matched filters permit time-bandwidth products of the order of 150 or less, and therefore a maximum processing gain of about 22 dB. The achievable processing gain for a given type of system will be considered later.

6.6.2 Narrowband Transmission Systems. Narrowband transmission systems are characterized by low bit rate and information bandwidth, compared to wideband systems. The system bandwidth B, is divided into channels each of bandwidth B/C, where C is the number of channels. The maximum matched filter processing gain for narrowband transmission is also B_I/B_R, where B_I is the information bandwidth and under ideal conditions (perfect filters, no frequency instabilities, etc.) is equal to $B/_C$. Also, if the number of sensors per channel is reasonably large (i.e., N >> 1) the maximum narrowband bit-rate bandwidth, B_{RN} is equal to the wideband bit-rate bandwidth, B_{RW} divided by the number of channels, C. Therefore, the maximum narrowband processing gain within each narrowband channel is the same as for a wideband system.

6.6.2.1 Message Length. To determine the maximum message length for the narrowband system, it will be assumed that each narrowband channel must accommodate up to 32 sensors. Using the same assumptions and parameters as for the wideband system the message length is found to be

$$8)\quad T_m \leq \frac{.01}{3X.005(32-1)} = 21.5 \text{ msec}$$

Letting T_m equal 20 msec., the bit period for the same 40-bit message becomes 0.5 msec/bit giving a narrowband bit rate, B_R of 2000 bits per second and a B_R of

$$9)\quad B_{RN} = B_R \text{ (Hz)} = 2000 \text{ Hz}$$

The information bandwidth, to obtain the same maximum processing gain as the wideband system, is found from

$$10 \log \left(B_I/_{B_{RN}} \right) = 26.5 \text{ dB} = 450 \text{ ratio}$$

or

$$10)\quad B_I = 450 \times 2000 = 900 \text{ kHz}$$

it is doubtful that one would consider this a narrowband system. Therefore, the obvious solution is to provide more available channels, and consequently obtain a greater sensor capacity or recover some anti-jamming margin against broadband jammers, by reducing the noise bandwidth of the receiver and therefore improving the (S/N) for a given input signal level and jammer power.

6.6.2.2. Matched Filter Limitations. Just as the wideband system is not able to take advantage of all the potential processing gain due to state-of-the-art capabilities in fabricating matched filters, neither is a narrowband system able to take advantage of all its potential gain because of: a) the frequency instabilities of the transmitter and receiver oscillators, which caused increased noise bandwidth, as well as non-coherent processing; and b) imperfect filters, which require guardbands between channels, etc. The magnitude of the degradation from a matched filter operation by non-coherent processing is a function of the ratio of frequency uncertainties to bit-rate-bandwidth. Glenn 2/ has performed an analysis on a narrowband digital data system in which the predetection bandwidth of the mark and space channel was a function of the source carrier frequency uncertainty. The ratio of this bandwidth to the bit-rate bandwidth (B_I/B_R) is assumed to be much greater than one, due to frequency uncertainties. The receiver consisted of a predetection filter (for Mark or Space) followed by an envelope detector and a filter matched to the bit rate, B_R. The data in Table II-I and Table II-II show a comparison of this non-coherent performance with a similar coherent system with an equivalent processing gain when B_I/B_R is equal to 10 and 100. As indicated from the tables, the performance of the non-coherent system improves relative to the coherent system as the input $S/_N$ increases for either B_I/B_R. At a bit error rate of 10^{-5} the deficit is about 3 dB, and as $E/_{b}n)$ becomes much greater than B_I/B_R the performance approaches the optimum FSK System.

6.6.2.3. Narrowband Bandwidth with Frequency Uncertainty. The minimum channel bandwidth (Bc) required for a narrowband system with bit rate bandwidth B_{RN} and frequency uncertainty $/\Delta F/$ is

11) $B_I \geq 2(B_{RN} + /\Delta F/)$

assume $/\Delta F/ = 10x10^{-6}x153x10^{6} = 1530$ Hz

and from 9

12) $B_{RN} = 2000$ Hz

2/ "Analysis of Non-coherent FSK Systems with Large Ratios of Frequency Uncertainties to Information Rates", A.B.Glenn,RCA DEP,Moorestown,N.J.

TABLE II-I

Comparison of Non-Coherent Performance with a Similar Coherent System - Equivalent Processing Gain = 10

B_I/B_R = 10; MAXIMUM PROCESSING GAIN = 10 dB

BIT ERROR PROB.	ENERGY-TO-NOISE DEN.	MATCHED FILTER INPUT	ACTUAL INPUT	DEFICIT
P_e	(E_b/η)	$(S/N)_i$	$(S/N)_a$	$[(S/N)_i-(S/N)_a]$
$1.5x10^{-1}$	0 dB	-10 dB	-2 dB	-8 dB
$3.x10^{-2}$	5 dB	-5 dB	1 dB	-6 dB
$5x10^{-4}$	10 dB	0 dB	4 dB	-4 dB
$1x10^{-4}$	11.2 dB	1.2 dB	4.9 dB	-3.7 dB
$3x10^{-5}$	12.0 dB	2.0 dB	5.2 dB	-3.2 dB
$1x10^{-5}$	12.5 dB	2.5 dB	5.5 dB	-3.0 dB

TABLE II-II

Comparison of Non-Coherent Performance with a Similar Coherent System - Equivalent Processing Gain = 100

(B_I/B_R) = 100; MAXIMUM PROCESSING GAIN = 20 dB

BIT ERROR PROB.	ENERGY-TO-NOISE DEN.	MATCHED FILTER INPUT	ACTUAL INPUT	DEFICIT
P_e	(E_b/η)	$(S/N)_i$	$(S/N)_a$	$[(S/N)_i-(S/N)_a]$
$1.5x10^{-1}$	0 dB	-20 dB	-7.5 dB	-12.5 dB
$3x10^{-2}$	5 dB	-15 dB	-4.5 dB	-10.5 dB
$5x10^{-4}$	10 dB	-10 dB	-2.2 dB	-7.8 dB
$1x10^{-4}$	11.2 dB	-8.8 dB	-2.0 dB	-6.8 dB
$3x10^{-5}$	12.0 dB	-8.0 dB	-1.8 dB	-6.2 dB
$1x10^{-5}$	12.5 dB	-7.5 dB	-1.7 dB	-5.8 dB

Therefore

$$B_I \geq 2(2000 + 1530)$$

$$B_I \geq 7060 \text{ Hz}$$

assume

$$B_I = 10 \text{ kHz}$$

then

$$B_I/B_{RN} = 5$$

It is therefore a reasonable assumption that the loss in processing gain for this narrowband system will be less than 3 dB, although the approximation made in the Glenn analysis requires a larger B_I/B ratio for the results to be valid.

The above bandwidth requirement assumes that the modulation is either AM or narrowband FM (or PM). If FSK modulation is used for the digital modulation, a minimum β of the order of 1 would be required to minimize Gaussian noise errors and spike errors at reasonable (S/N) ratios 3/ therefore, channel bandwidth Bc would be a minimum of about $2B_I$ or approximately 20 kHz under the above assumptions.

6.7 System Types. In order to make a more definitive comparison between wideband and narrowband transmission techniques, two types of system implementation will be selected for each technique and pertinent parameters will be determined for each of these types from which additional comparisons can be made.

6.7.1 Wideband System Types. The types of wideband systems to be evaluated are: PNSS and FFH.

a) PNSS - This is a wideband type in which the instantaneous bandwidth is generally equal to the total system bandwidth. That is, the energy of each transmitted code bit is spread over the band, although not of uniform spectral density. Each information bit is coded with a PN code whose bit rate is sufficient to provide the desired degree of band-spreading. Ideally, the length of the PN code would be sufficient to resemble a noise burst with periodicity. However, in practice the length of the code is not usually an independent parameter if matched filter processing is desired.

b) FFH - This type may also be considered a spread spectrum technique. However, it differs from the PN technique in that only a portion of the system bandwidth is utilized in each code bit transmission, but the carrier frequency is switched after each code bit transmission so that the total system bandwidth is utilized (usually) during a given message transmission.

3/ "Error Rates for Digital Signals Demodulated by an FM Discriminator", Donald L. Schilling, et al. IEEE Trans. on Comm. Tech., Aug. 1967.

The desired information bandwidth is obtained by coding in a similar manner to PNSS. A tradeoff must be made between the obtainable processing gain per information bit and the number of separate frequencies available for hopping.

6.7.2 Narrowband System Types. The types of narrowband systems to be evaluated are SFH and FD, sometimes referred to as the Frequency Division Multiplex (FDM) System.

a) SFH - This is a narrowband type in which the system bandwidth is divided into several narrower bands. Each transmitter switches from one channel to the next in a predetermined order until all assigned channels have been utilized. The number of assigned channels may be all available channels or it may be a particular set of the total number. The rate at which channels are selected (hop rate) may be approximately equal to, or somewhat less than the average message rate. It may have all the other characteristics of the FDM narrowband system.

b) FD - In this type of system, the system bandwidth is also divided into many channels whose bandwidth is sufficient to accommodate the required data rate and modulation method. Each device transmitter is assigned to a channel and remains on the channel for all its transmission life. This is the major difference in FDM and SFH.

6.8 Evaluation of Candidate Systems. Each of the system types will be analyzed in terms of common performance parameters.

6.8.1 Processing Gain. Processing gain is defined as the improvement in (S/N) of the desired signal as it is processed and detected in the receiver. Processing gain may be used to a) reduce the required receiver (S/N) for a specified error performance; b) increase the transmission range for a given transmitter power; or c) provide a margin of anticipated noise sources. Against a noise jammer, it provides a so called AJ margin. Regardless of the system type, the maximum available processing gain is equal to the product of the message duration and the system bandwidth. For practical reasons, the maximum processing gain is seldom achieved.

a) PNSS - The limitations of analog matched filter processors for burst type messages has already been discussed. To provide the maximum number of sensor for a given self-interference probability, each message bit will be coded to provide the maximum processing gain per bit and transmitted once, therefore, no additional processing gain is available from post-detection processing. Assuming the maximum $T_B B_P \approx 150$ for a PNSS system gives a processing gain of

$$13)\ G_P = 10 \log T_B B_P = 10 \log 150 \simeq 21.8 \text{ dB}$$

where

B_p = Pseudo-noise transmission bandwidth

T_B = Message bit duration

and since

B = 15 MHz = System Bandwidth

$T_B \leq 10$ usec per bit

and

14) T_m = 40x10usec = 400 usec

= message duration

if

N = chips per message bit

then

τ = chip duration = T_B/N

The closest PN code to the assumed $T_B B$ product is

N = 151

Therefore

15) $\tau = \frac{10X10^{-6}}{151}$ sec = .066 usec/chip

and the chip rate, Rc is

16) $R_c = \frac{1}{\tau} = \frac{1}{.066 \times 10^{-6}} = 15.1$ MHz

The data bit rate, R_D, is

17) $R_D = \frac{1}{T_B}$ = 100 K b/s

giving a bit-rate bandwidth requirement of

$B_R = R_D$ (Hz) = 100 kHz

or

10 log B_e = 50 dBHz

b) FFH - The FFH system divides the available system bandwidth into a set of equally spaced frequencies and the spacing gives the maximum information bandwidth per transmission. The potential processing gain is then a tradeoff between the number of separate bands used and the allowable time for each transmission. If a separate frequency band is selected for each message bit, the bandwidth per bit becomes 375 kHz. With the practical limitation on analog matched filters of about 20 usec/bit the processing gain per bit then is only about 8.7 dB. This would give a message time of 800 usec. To achieve a higher processing gain it will be assumed that the system bandwidth is divided into three, 5 MHz, segments. All three frequencies (f_1, f_2, f_3), properly modulated, will be sent each data bit time with one sequence of frequencies representing a binary digit '1' and an alternate sequence representing the binary digit '0'.

18) $S = 3$ = Sub-bits per message bit

$$B_F = \frac{15\text{ MHz}}{3} = 5\text{ MHz} = \text{FFH transmission bandwidth}$$

$$T_{SB} = 20\text{x}10^{-6}\text{ sec} = \text{Sub-bit duration}$$

Therefore, the FFH processing gain is

19) $G_p = 10 \log T_{SB} B_F = 10 \log 100 = 20$ dB

and the 40 bit message duration is

20) $T_m = 3\text{x}40\text{x}20\text{x}10^{-6} = 2400$ usec

The closest PN code to the assumed T_{SB} B_F product is

$N = 103$

Therefore

21) $\tau = \dfrac{20\text{x}10^{-6}}{103} = .194$ usec/chip

The chip rate is therefore

22) $R_c = \dfrac{1}{\tau} = 5.15$ MHz Mbp/sec

The data bit rate is

23) $R_D = \frac{1}{3T_{SB}} = \frac{10^6}{60} = 16.6$ Kb/sec

from which the data bit-rate bandwidth is

$$B_D = R_D \text{ (Hz)} = 16.6 \text{ kHz}$$

or $10 \log B_D = 42.2$ dBHz

and the code bit-rate bandwidth is

$$B_R = \frac{1}{T_{SB}} = 50 \text{ kHz}$$

or $10 \log B_e = 47$ dBHz

With the redundant transmission of three sub-bits per message data bit, matched filter processing, followed by digital processing of the three sub-bits, can reduce the required (S/N) per sub-bit, although a net energy loss will result when compared to matched filter processing of the full data bit.

c) SFH/FD - The SFH and FD narrowband system types are similar in most respects, since similar modulation and demodulation characteristics would be applicable to each. Although modulation methods will be evaluated and compared as a separate exercise, it will be assumed for this evaluation that FSK would be used for the SFH and FD systems. Therefore, the processing gain to be expected in the receiver depends on the channel bandwidth for a given bit rate and frequency uncertainty. From previous consideration it is estimated that a minimum processing gain per channel of 8 dB may be obtained, providing the input (S/N) is reasonably high $>$(10 dB)

6.8.2 Required Output Signal-to-Noise Ratio (S/N). The signal-to-noise ratio required at the decision device (to reconstruct the modulating signal, m(t)) depends upon various allowable error probabilities which may in turn depend upon the structure of the message. In addition any redundancy in the message due to coding is also significant.

If the receiver could decide when the signal-to-noise ratio was sufficient to permit the decoding to take place within the allowable error rate, it could squelch the signal into the decoder until the (S/N) was adequate for the decoding reliability required, then process the incoming signal. Alternatively, the message can be coded with a preamble from which the subsequent decoding of the message would depend on receipt of the correct message preamble. For purposes of comparison, the latter case will be assumed. An eight bit preamble will be assumed for message detection and false alarm probability evaluation, from which the required (S/N) can be determined. Subsequent probability of bit error will then be evaluated, given that a message is present.

a) PNSS - The reference PNSS system utilizes a 151 chip PN code per message data bit. To evaluate false alarm and detection probability let

P_{DM} = Prob. of message detection (Preamble Detection) given that a message was sent

P_{DB} = Prob. of data bit detection

then

24) $$P_{DM} = \sum_{i=6}^{8} \binom{8}{i} \left(P_{DB}\right)^{i} \left(1-P_{DB}\right)^{(8-i)}$$ (6 out of 8 correct bits in the Preamble)

$$= 56\, P_{DB}^{6} \left(1 - 1.86\, P_{DB} + .875\, P_{DB}^{2}\right)$$

but

P_{DM} = 1-(Prob. of message dismissal due to noise only)

= 1 - .01 = .99 (specification)

therefore, from 24)

25) $P_{DB} \simeq .924$

To determine false alarm probability let

FAD = expected false alarm per day

P_{FAM} = prob. of message false alarm

P_{FAB} = prob. of data bit false alarm

P_c = prob. of false alarm during chip time

The probability of message false alarm, P_{FAM}, is based on the assumption that if six data bit false alarms occur within a time interval equal to eight data bits, given that one false alarm has occurred, then a message will be declared and therefore a message false alarm will have occurred.

26) $P_{FAB} = 151\, P_c$

and a message false alarm will occur with a probability of

27) $$P_{FAM} \simeq \binom{8}{6}\left(P_{FAB}\right)^{6}$$ (six false alarm bits out of 8 bit times)

since

$P_{FAB} << 1.$

Also

28) FAD $= (P_{FAM})$ x (message opportunities per day)

$= P_{FAM} \times 8.64 \times 10^4 \quad \frac{1}{80 \times 10^{-6}}$

but

FAD $\leq$ 1 (specification

therefore, from 26, 27 and 28:

29) $P_c = 10^{-4}$

Using the detection and false alarm parameter values from 25 and 29, the required (S/N) is found to be

30) $(S/N)_{PNSS} \simeq 12$ dB (Receiver sensitivity = -103 dBm)

The digital processing gain resulting from the preamble is found to be approximately 3.3 dB. Therefore, if matched filter processing could have been performed directly on the eight bit preamble, the required preamble E_b/η) would have been 15.3 dB. Since the (S/N) given by 30 may be equated to the energy per bit to noise density (E_b/η) the power required is greater when a matched filter per bit is followed by digital processing, and, therefore, the processing loss is

31) Loss $\leq$ $|15.3 \text{ dB} - 12 \text{ dB} - 10 \log (8) \text{ dB}| = 9.3$ dB

Once a message has been detected (with a given confidence) the prior knowledge about the message (bit rate, length, etc.) permits the subsequent evaluation of the bits (as being either a '1' or '0') to be made with greater confidence, or with a smaller probability of error. With matched filter processing of the data bits ohe bit error probability, with the E_b/η given by 30, is less than 10^{-8}, and therefore the total message error probability of 4×10^{-3} for a string of three repeaters plus a UCR is easily met.

b) FFH - The reference FFH system utilizes three PN code bits per message bit with each code bit containing 103 chips. Using the same preamble and processing criteria as before, the required probability of detection per data bit is still .924. However, since there are now three code bits per data bit, and the probability of detecting a code bit is the criterion which will determine the E_b/η per code bit, digital processing of the code bits is possible. The optimum choice is two out of three code bit detections for a data bit detection: 4/ With these constraints, the required probability of detection per code bits is

32) $P_{DCB} = .831$

4/ Schwartz, M. "A Coincidence Procedure for Signal Detection," Trans. IRE, Vol. IT-2, No. 4, Dec 1956.

and the allowable false alarm probability per chip is about 7×10^{-4} but will be assumed to be 10^{-4}, as with PNSS. The required (S/N) is then determined to be

33) $(S/N)_{FFH} \approx 11.2$ dB (per PN code bit) (Receiver sensitivity = -107.1 dBm)

Whereas the energy per code bit has been reduced by 0.8 dB vs. PNSS, the energy per data bit has been increased by about 4.8 dB. Much of this difference results from the fact that the processing time cannot be increased to compensate for the reduced bandwidth of the FFH code bits, due to practical design limitations.

c) SFH/FD - These system types are again considered equal for the purpose of the (S/N) requirement. There will be one bit per data bit and it is assumed that message preamble and preamble processing is the same as for the PNSS and FFH. Therefore, the probability of detection per data bit will be identical with the PNSS. That is

34) $P_{DM} = .99$ (specification)

35) $P_{D_B} = .924$ (see 24))

The bit false alarm requirements will be different due to the bit-rate bandwidth, B_R, differences. For the B_R given by 12, the probability of false alarm per bit is about 1.5×10^{-2}. For purposes of this relative comparison it will be assumed that the bit false alarm probability can be no greater than 10^{-2} giving a required S/N of

36) $(S/N)_{NB} \geq 9.8$ dB

Although the probability of false alarm per opportunity given above meets the message false alarm probability requirement of 1 false alarm per day (FAD), in practice, the decision threshold would be set to provide a P_{FAB} of about 10^{-4}. With the same missed message requirement, the required S/N or E_b/η would be increased to about 12 dB. The actual value may be determined by the bit error probability requirement (see next section).

6.8.3 Error Probabilities. Once the message has been detected, with the desired confidence, by declaring that the preamble has been received, the prior knowledge about the message (bit rate, length, etc.) may be used to aid in decoding the message. In order to estimate the subsequent error probability during decoding at the given E_b/η, additional information must be available, namely, what modulation method is used.

For the PNSS and FFH system, a SWD will be assumed for coding and modulating the data bits producing a PSK output at the respective chip rate. Since a complementary device will be used in the receiver, the resultant system is approximately equivalent to a coherent PSK system from which the relation between the error probability and bit energy-to-noise density in the receiver is given by

37) $$Pe = \frac{1}{2}\left[1-\text{erf}\ \sqrt{E/\eta}\right]$$

For the SFH/FD systems, an FSK non-coherent, "matched" filter envelope detector/processor will be assumed for comparison purposes. Performance of practical filters need be no worse than about 1 dB less than matched filters, so the above assumption is not too farfetched. For this case, the probability of error becomes

38) $$Pe = \frac{1}{2}\ \exp\left[-\frac{E_b}{2\eta}\right]$$

a) PNSS - Using the relation 37 and the value of (S/N) given by 29, the error probability after message detection becomes

39) $$Pe_{PNSS} = \frac{1}{2}\left[1-\text{erf}\ \sqrt{15.9}\right] = 8.5 \times 10^{-9}$$

b) FFH - Using the relation 37 and the value of 32, the error probability after message detection becomes

$$Pe_{FFH} = \frac{1}{2}\left[1-\text{erf}\ \sqrt{13.2}\right]$$

$$= 1.4 \times 10^{-7}$$

c) SFH/FD - Using the relation 38 and the value of (S/N) given by 36, the error probability after message detection becomes

$$Pe = \frac{1}{2}\ \exp\left[-\frac{9.55}{2}\right]$$

$$= 4.2 \times 10^{-3}$$

This error probability is not sufficient to meet the link requirements listed previously. To obtain a Pe of 3×10^{-5} or less, as required, the (S/N) must by increased to about

$$(S/N) \approx 13 \text{ dB} \qquad (SFH/FD)$$

(Receiver sensitivity = -119.3 dBm)

When the decision threshold is set for the same message detection probability with this (S/N), a false alarm would almost never occur. Two altnatives are possible: 1) the message detection probability may be increased, thereby increasing the bit false alarm probability but still maintaining the expected false alarm of one per day. or 2) the preamble may be reduced from eight bits to three bits which would still maintain the required detection and false alarm probabilities.

With a three-bit preamble and a two-out-of-three digital processor for message detection, the required bit detection probability becomes

41) $P_{DB} = .941$

With the threshold set for the P_{DB} at a (S/N) of 13 dB, the bit false alarm becomes

42) $P_{FAB} = 1 \times 10^{-5}$

which is sufficient to meet the message false alarm per day requirements.

This (S/N) of 13 dB will be used instead of 36 for the narrowband systems. Error performance for all alternatives is given in Table II-III.

TABLE II - III

DETECTION, FALSE ALARM, AND ERROR PERFORMANCE

ALTERNATIVE	PREAMBLE BITS	OUTPUT (S/N) $(E_b/n)_o$	PROB. MSG. DET. P_{DM} (1)	PROB. MSG. FALSE ALARM PER DAY P_{EAD} (1)	RECEIVER SENSITIVITY	PROB. OF BIT ERROR Pe (2)
A. NARROWBAND						5
(1) SFH/FD	3	13 dB	.99	< 1	-119.3 dBm	$2.2x10^{-5}$
B. WIDEBAND						8
(1) PNSS	8	12 dB	.99	< 1	-103 dBm	$8.5x10^{-9}$
(2) FFH	8	11.2 dB	.99	< 1	-107.1 dBm	$1.4x10^{-7}$ 6/7

(1) Specification values.

(2) Required Pe for single receiver is $1.25x10^{-4}$. Worst cast Pe for three repeaters plus UCR is $3.1x10^{-5}$.

6.8.4 Transmitter Power Requirements. A fundamental measure for comparing the various transmission techniques is the transmitter power required to meet the same performance requirements in a given environment. There is a limit to the amount of power which the battery is capable of providing, or given that the battery can provide the power, the expected life of the sensor, relay, etc., is a function of the transmitter power requirement. For the sensor, the power will be determined based on an estimated loss for a 15 km line-of-sight distance to the repeater. For the repeater, a 60 km range will be assumed. Path loss for these ranges assumes a European-type terrain with the device antenna characteristics as shown in Table II-IV.

TABLE II-IV

Device Antenna Characteristics

DEVICE	ANTENNA HT	ANTENNA GAIN	Lp, MEAN PATH LOSS
UCR	13 meters	2 dBi	——
Repeater	13 meters	2 dBi	158 dB/60 km
Sensor	1 meter	0 dBi	145.6 dB/15 km

Other parameter values which will be used for determining power requirements are:

T_A = Antenna Noise Temperature = 1300°K (ambient)

L = Filter and Cable Losses = 1.5 dB = 1.42 ratio

F = Receiver Noise Figure = 4.5 dB = 2.82 ratio

Te = Equivalent Noise Temperature = T_A + (LF-1) 290° K

$\eta \frac{dBm}{Hz}$ = Receiver Noise Density = 10 log kT_e = 165.3 dBm/Hz

α (r) = Net Loss from Transmitter Output to Receiver Terminals

= (Path Loss) - Σ (Antenna Gains) = $L_P - G_{AT} - G_{AR}$

Sensor-to-Repeater or UCR:

43) α (r) = -0 + 145.6 dB - 2 + 143.6 dB

Repeater-to-Repeater or UCR:

44) α (r) = -2 + 158 dB - 2 = 154 dB

6.8.4.1 Ambient Noise Environment. The peak transmitter power requirement for the sensor and repeater transmitter will be determined for an assumed noise environment only. Pertinent parameter values are given in Table A-I 5/ with the resultant power values.

a) Wideband Systems - The PNSS and FFH power requirements are determined from equation 6 on the assumption that a surface wave device (SWD) is used for coding and decoding the messages.

b) Narrowband Systems - Power requirements for the SFH and FD systems are determined from equation 1, assuming a non-coherent FSK modulation with frequency uncertainty. Therefore, the $(S/N)_{IF}$ required to obtain the Eb/η of 13 dB would be about 5 dB. This accounts for the approximate 2 dB loss in the detector against the potential 10 dB of processing gain due to bandwidth reduction.

6.8.4.2 Noise Jammer. A/J Margin. (Classified) 5/

6.8.6 Spectrum Utilization. The ability to operate REMBASS sensors in the presence of other co-band users has been briefly addressed under the condition of RFI susceptibility for each of the transmission techniques. In view of the short duration burst nature of sensor signals it is not likely that these would cause significant interference with other users of the same RF spectrum as REMBASS, regardless of the transmission technique. This has proven to be the case with Phase III sensor signals. Therefore, spectrum utilization will be considered from the standpoint of REMBASS alone.

6.8.6.1 Number of Available Channels

a) PNSS/FFH - Both wideband transmission types utilize the full system bandwidth during each transmission, therefore only one channel is available for all sensors.

b) SFH/FD - On the basis of previous assumptions concerning modulation method, bit rate, etc., the required bandwidth per channel is 20 kHz. With a 15 MHz system bandwidth, this would provide 750 channels for the narrowband transmission technique. To minimize co-channel interference and simplify hardware design, it will be assumed that only alternate channels are used which would provide 375 usable channels.

6.8.6.2 Total Number of Sensors

a) PNSS - The total number of sensors accommodated by the wideband PNSS system may be determined from 7. The message duration (40 bits) is given by 14.

5/ Sections 6.8.4.2 thru 6.8.5.5 including Tables A-I, A-II & A-III are in Classified Addendum A.

$$n \simeq \frac{P}{3\lambda Tm} \qquad (n>>1;\ \lambda Tm<<1)$$

$$P = .01$$

$$\lambda = .005$$

$$Tm = 400 \quad 10^{-6}$$

$$n \simeq \frac{.01}{3 \times .005 \times 400 \times 10^{-6}}$$

$$n = 1670 \text{ sensors}$$

b) FFH - The message duration for the FFH system is 2400 usec, therefore

$$n = 278 \text{ sensors}$$

c) SFH - To determine the number of sensors which the SFH system can accommodate, one must select the number of channels in the hopping sequences. This set of channels then becomes a "hopping channel". The number of "hopping channels" is found by dividing the number of channels in the sequence into the total number of channels. Since there can be no more than 32 sensors (on the basis of previous calculation) per "hopping channel," the number of sensors accommodated by the SFH is inversely proportional to the number of channels in the hopping sequence.

Assume that each "hopping channel" consists of a specified set of 7 channels arbitrarily distributed over the system bandwidth. There will then be

$$\frac{375}{5} \simeq 50 \text{ "hopping channels"}$$

With 32 sensors per "hopping channel," the SFH can accomodate

$$50 \times 32 = 1600 \text{ sensors total.}$$

If a set of 5 channels is selected per "hopping channel," the number of "hopping channels" becomes 75 and the total number of sensors is increased to 2400 total. For comparison purposes, it will be assumed that a set of 5 channels is used for a "hopping channel".

d) FD - The message duration for the channelized system was based on 32 sensors per channel. If all 375 channels are usable (which is unlikely), the total number of sensors which may be accomodated by the narrowband FDM technique is

$$n = 375 \text{ channels} \times 32 \frac{\text{sensors}}{\text{channel}}$$

$$= 12{,}000 \text{ sensors}$$

Although there will never be a requirement to deploy 12,000 sensors at a given time, having this capability permits a greater flexibility for assigning sensor ID in addition to reducing self-interference between sensor transmissions in areas of higher-than-normal activity. (See Table II-V and II-VI).

TABLE II-V

SPECTRUM UTILIZATION

AVAILABLE CHANNELS & TOTAL SENSORS			
SYSTEM TYPE	AVAILABLE CHANNELS	TOTAL SENSORS	
WIDEBAND			2
(1) PNSS	1	1670	
(2) FFH	1	278	1
NARROWBAND			4
(1) SFH	75 "Hopping Channels" (see Note)	2,400	
(2) FD	375	12,000	10

Note: A "hopping Channel" is a set of 5 channels used in a hopping sequence by a given set of 32 sensors or less.

TABLE II-VI

PERFORMANCE

ALTERNATIVE	ERRORS	ECM+RFI	RELIABILITY	SPECTRUM UTILIZATION		POWER REQUIREMENTS	RELATIVE RANK
				CHANNELS	SENSORS		
	( )*	( )*	( )*	( )*	( )*	( )*	
A. NARROWBAND SYSTEMS							
(1) SFH							
(2) FD							
B. WIDEBAND SYSTEMS							
(1) PNSS							
(2) FFH							

* ( ) Rank of individual criterion to be determined.

Note: Data for this table will be generated by analysis of individual criterion in previous tables.

6.8.7 Versatility (See table II-VII). The versatility of the transmission techniques will be compared on the basis of the ability to transmit analog data messages in addition to digital data messages. The measure of comparison will be the relative increase in equipment requirements necessary to transmit the analog data in the most expeditious manner. A logical assumption applicable to all systems in that analog data transmission will only be required from a limited number of sensors and then only on command.

Two possibilities exist for digital transmission of analog data over the wideband systems: a) pluse code modulation (PCM); or b) delta modulation (DM). Quantization noise $(S/N)_q$ is inversely proportional to the number of levels of the PCM code and to the bit rate for DM. For bit rates up to about 40 Kb/s, DM provides a better signal-to-quantization noise ratio than PCM but for higher bit rates, PCM outperforms DM from the standpoint of $(S/N)_q$. An additional advantage with DM is that a single bit error can cause only minor distortion in the output, whereas a bit error in PCM may cause an equivalent noise spike of from the least incremental level to full amplitude, depending on which bit is in error. Therefore, DM will be the mode of transmitting analog data using the PNSS wideband technique, and may be applicable to FFH also.

For the narrowband systems, direct transmission of the analog data will be considered using linear FM.

a) PNSS - By using the same word length, message rate, etc. as used for digital data, only the sensor would be modified for transmission of analog data using DM. Assuming that 21 bits of the message may be used for transmitting the DM data, an average bit rate of 21 x 833 = 17.5 Kb/sec may be obtained. With this data rate, the signal-to-quantizing noise ratio (S/N)q will range from about 10 dB at the upper analog frequency to about 25 dB at the lower frequencies. Observations on commercial telephone circuits have indicated a (S/N)q of at least 26 dB is required for acceptable performance. The additional circuitry required in the sensor is relatively minor, consisting of a pulse generator, digital modulator, comparator and integrating network. In order to increase the signal-to-noise ratio, the average bit rate would have to be significantly increased. This would require modification of all equipments to accommodate combined analog and digital data transmission interchangeably.

b) FFH - The performance and equipment modifications would be essentially the same for the FFH system as for PNSS. An alternate technique for analog data is shown in Figure 2-6 in which analog data is transmitted by linear FM over a selected narrowband channel similar to the narrowband technique.

c) SFH - Adding an analog capability to the SFH system would require some equipment additions and modifications. Linear analog transmission from the sensor would mean that the sensor must switch to a separate channel and operate in the same way as the channelized FD for the duration of the transmission. A separate and distinct analog relay would be required in addition to a separate UCR.

Therefore, the added cost and system complexity would be significant. Whereas the (S/N) of a quantized digital system is more or less constant and independent of the number of repeaters between the sensor and the UCR, linear analog modulation would suffer a degradation of (S/N), as well as dynamic range through each repeater. It is doubtful that the (S/N) of the SFH system would be any better than the digitized systems which use the same word length and message rate in their digital message design.

d) FD - Adding an analog capability to the channelized FD system would be less expensive than for the SFH system. Only a linear modulator would be added to the sensor (not counting the command receivers, etc., which would be required of all systems since the same channel frequency and transmitter would be used on both digital and analog). In the repeaters, a discriminator and linear modulator would be required if a baseband repeater is used. Otherwise, a mixer would be required if an IF repeater is used, to translate from the IF up to the output frequency. A separate output frequency would be required if a combined digital/analog repeater was used. The analog repeater could serve to relay both analog and digital data, if desired. A similar degradation of the signal would occur through each repeater as with SFH and therefore may be as bad or worse than a wideband unmodified digital system.

Due to the dual use capability of sensor components and repeaters, the added cost of the FD system would be less than SFH.

The (S/N) performance of the narrowband systems may be approximated, using the same channel characteristics as for digital data transmission.

The IF bandwidth is given as 20 kHz. This full bandwidth may be used for the analog signals. Using Carson's Rule for the bandwidth required for linear modulation

$$20 \text{ kHz} = 2 f_m (1 + \beta) + 2/\Delta f/$$

f_m = highest analog frequency

= 2000Hz

$/\Delta f/$ = frequency uncertainty = 1530 Hz

Therefore,

$$\beta = 3.25$$

If the repeater and UCR use an FM discriminator for demodulation of the analog signals, a (S/N) improvement may be obtained provided the input S/N is above the threshold (about 10 dB). This is approximately

$$(S/N)\ \text{Improvement} \approx 3\beta^2 \frac{B_{IF}}{2fm}$$

$$= 3\ (3.25)^2 \times \frac{20\ \text{kHz}}{2\text{x}2\ \text{kHz}}$$

$$\approx 158 = 22\ \text{dB}$$

From previous computations, it is clear that the required input (S/N) cannot be maintained without sacrificing some A/J margin. However, with no jamming and under the previous assumption of receiver noise and transmitter power, the improvement factor above may be realized. Where three repeaters are cascaded, dynamic compression and increased noise level may reduce the (S/N) at the UCR by 6 dB or more. Therefore, the (S/N) performance of the narrowband systems may range from 26 dB to 40 dB, with a more likely value of 32 dB. On performance alone, the narrowband systems are somewhat superior to the digitized wideband systems which have been optimized for digital data instead of analog data.

TABLE II-VII

VERSATILITY

ALTERNATIVE	CAN SYSTEM TRANSMIT ANALOG AND DIGITAL	MODIFICATIONS NECESSARY	EXPECTED S/N FOR ANALOG	MISCELLANEOUS COMMENTS
A. NARROWBAND 1. SFH	(Note 1) 10 Yes	9 Moderate amount of equipment mods.	10 26 - 40 dB	No significant A/J protection for analog data
2. FD	10 Yes	10 Very little	10 26 - 40 dB	(Same as SFH)
B. WIDEBAND 1. PNSS	10 Yes	5 Moderate increase in transmitter section; Sizeable increase in receiver (30% increase in Tx) (50% increase in RX)	5 Signal-to-quantization ratio of - 10 dB - 25 dB	This (S/N)q is not considered adequate for good analog communication
2. FFH	10 Yes	3 Approx. 40% increase in both transmitter and receiver sections	10 26 - 40 dB	(Same as SFH)

Note 1. Relative rank of each alternative is given by a number between 0 - 10. The larger number indicates higher ranking.

6.8.8 Reliability (see Table II-VIII). Since reliability is usually related to hardware performance, it is not really meaningful to speak of reliability in connection with transmission techniques. However, the influence of a particular type of transmission system on the subsequent complexity of the communication hardware could be related to reliability indirectly. Nevertheless, reliability could only be considered in a relative manner, rather than a mean-time-to-failure (MTTF) or some other standard measure of reliability. Similar types of components would be used in all systems except, perhaps, the analog surface wave devices for the wideband systems. Since the wideband techniques require more transmitter peak power than the narrowband techniques, it is possible that this could result in a potentially less reliable sensor and repeater for the wideband systems. The FFH system requires three times the amount of coding and decoding equipment as compared to the PNSS system and, therefore, would possibly be ranked below PNSS for the wideband systems.

Of the narrowband systems, the SFH requires synchronization between the individual transmitters and receivers. In view of the frequency stability problems of reference oscillators, even if synchronization could be obtained in some way initially, it is doubtful that it could be maintained for reasonable length of time. Therefore, a means of synchronization would have to be included in the system. The logical means would be a command link to each repeater and sensor. This necessitates additional equipment, and, consequently, a less-reliable system. In view of this, it is expected that the SFH may be less reliable than either of the wideband systems. It is, of course, axiomatic that the long term synchronization problem is reduced in direct proportion to the increase in hopping period. However, the initial synchronization problem would still remain.

TABLE II-VIII

RELIABILITY (RELATIVE)

ALTERNATIVE	RELATIVE RELIABILITY	(Note 1)
A. NARROWBAND		
(1) SFH	Likely to produce the least reliable system, because of synchronization problems.	1
(2) FD	Due to relative simplicity, and least peak power requirements, would probably result in the most reliable system.	10
B. WIDEBAND		
(1) PNSS	Potentially most reliable of the wideband type. Because of high peak power requirements it would likely result in a less reliable system than FDM but better than SFH.	4/6
(2) FFH	Potential reliability about 50% of PNSS, but somewhat better than SFH.	2/5

Note 1. Relative rank of alternatives.

6.8.9 Schedule (See Table II-IX).

6.8.9.1 Development Time

a) PNSS - Based on the use of Surface Wave Devices (SWD) as complementary matched filters, the performance indicated in this evaluation can be achieved with little additional development effort. However, in view of the excessive peak power requirements to provide the A/J margin indicated, it is imperative that additional processing gain must be obtained to reduce the power requirements. To get a significant increase in processing gain with SWD's would probably require a significant increase in processing gain with SWD's would probably require a significant development effort of two years or more. A corresponding development effort would be necessary to develop, or improve, batteries to provide the highpeak current requirements which are inherent in wideband systems.

b) FFH - The high peak power requirements of PNSS are also a characteristic of FFH since it is also a type of spread spectrum system. Therefore, the development requirements of the two would be essentially the same.

c) SFH - As noted previously, synchronization of the system transmitters and receivers is the major operational problem with this technique. To preclude the use of a command link to all devices, it would be necessary to develop very able clocks. This is not so much of a problem for equipments which have sufficient power available so that temperature control of crystal oscillators is possible. Since power is not available for this purpose in sensors and repeaters, some other means must be developed to accomplish this. It has been estimated that an update, or resynchronization, of all clocks would be required about once every 26 days with $\pm$ 5 ppm clocks. Clocks of this stability are not commercially available in quantities at a reasonable price. Therefore, a development effort is necessary to satisfy this requirement. More stable clocks will be required to meet REMBASS requirements if a link to all devices is not available.

d) FD - The technology to meet the requirements of REMBASS (with the exception of certain types of ECM) is currently available. Added performance could be obtained if more stable frequency sources were developed; however, this is not necessary. It does not seem to be cost effective to try to develop a system to meet all the postulated ECM threat when one considers that the threat is not well defined, and in addition, if the system was designed to overcome the expected threat, the duration of this superiority would probably be shortlived. It is concluded that the FDM technique would require the minimum development of all the techniques considered.

TABLE II-IX

SCHEDULE

ALTERNATIVE	DEVELOPMENT TIME
A. NARROWBAND	(Note 1) 5/7
(1) SFH	Moderate to Long. Development of a more stable clock required to meet synchronization needs in lieu of a command system.
(2) FD	10 Short to Moderate. Repeater development is major R&D activity but this is true regardless of which technique is used.
B. BROADBAND	3/5
(1) PNSS	Long. Considerable development effort required to increase processing gain capabilities of SWDs. Also possible development required to improve batteries.
(2) FFH	3/5 Long. Development requirements similar to PNSS.

Note 1. Relative rank of alternatives

6.8.10 Risk (See Table II-X). The risk associated with either of the transmission techniques is almost exclusively in the engineering, or advanced, development area.

6.8.10.1 Development Risk

a) PNSS - If this system is specified to provide either the processing gain to reduce the transmitter power requirements, or to provide the battery necessary to provide the power necessary with the currently available processing gain capability, the development risk would have to be considered high in either case.

b) FFH - The development risk associated with this system would be comparable to PNSS due to the similarity of the two techniques.

c) SFH - The primary risk associated with SFH is in development of a high stability clock. Since there is a cost performance trade-off here, the risk would only be considered moderate. In other words, if the desired stability could not be obtained, a shorter expected sensor (repeater) life could be accepted as an alternative.

d) FD - On a comparative basis, the risk associated with this system type is considered to be least since no unique developments are expected. Most of the development efforts would likely be those which are common to all techniques.

TABLE II-X

RISK

ALTERNATE	DEVELOPMENT RISK	(Note 1)
A. NARROWBAND		
(1) SFH	Moderate. Development of a clock to meet the required stability is considered to be somewhat difficult.	8
(2) FD	Low. FDM system to meet REMBASS requirements would utilize much of the capability of SEAOPS. No major unique development required.	10
B. WIDEBAND		
(1) PNSS	High. Extending the state-of-the-art in surface wave devices to obtain additional processing gain is considered to be questionable.	4/6
(2) FFH	High. Reasoning same as for PNSS.	4/6

Note 1. Relative rank of alternatives.

6.8.11 Logistics (See Table II-XI).

6.8.11.1 Test Equipment Requirements. Only unique test equipment requirements will be considered.

a) PNSS - The test equipment required for servicing equipment of this system would only be moderately extensive. Special test generators and receivers could be made from standard equipment components, such as SWD's and transmitter and receiver modules.

b) FFH - The test equipment for servicing this system would be slightly more complex than for the PNSS, but standard equipment components could be used for building the test equipment.

c) SFH - The test equipment requirements for the SFH would probably be more complex than either of the other systems due to the necessity for providing and maintaining synchronization of the hopping frequency.

d) FD - No unique test equipment would be required for this system. A general automatic test equipment made up of standard commercial components should provide the necessary servicing capability. Therefore, the test equipment requirement for FD is considered to be minimal.

6.8.11.2 Maintenance Skills Required. In general, it might be expected that technical expertise required by maintenance personnel would be of equal level. This is considered to be true for the PNSS and FD system types in particular. Due to the nature of the frequency hopping systems, they are assumed to be somewhat more complex from the standpoint of equipment calibrations and fault isolation. However, the FFH and SFH should be considered only slightly more demanding in maintenance skills required.

6.8.11.3 Equipment Adjustments Required. The PNSS, FFH, and FD systems require no special adjustments of equipments prior to, or during, operation. The SFH would require an initial synchronization of frequency and hopping rate, as well as possible readjustments during its operating life, either automatically or manually.

TABLE II-XI

LOGISTICS

ALTERNATIVE	TEST EQUIPMENT REQ.	MAINTENANCE SKILLS REQ.	EQUIPMENT ADJUSTMENTS REQ.
A. NARROWBAND	(Note 1) 3/5	6/8	3
(1) SFH	More complex than other system types.	About the same as FFH but somewhat greater than PNSS and FD	Adjustments required. Performance in this category possibly least of all systems considered.
(2) FD	No unique requirements. Equal to or less than other system types. 10	No special skills other than knowledgeable communication technician equal to PNSS. 10	No special adjustments. 10
B. WIDEBAND	7/9	10	10
(1) PNSS	Only slightly more complex than FD. No major unique test equip. requirements.	Same as FD	No special adjustments.
(2) FFH	Somewhat more complex than PNSS but less than SFH, assuming SWDs used for detecting hopping frequencies for the FFH. 6/7	More skills required than with FD and PNSS. Equal with SFH. 6/8	No special adjustments. 10

Note 1. Relative rank of alternatives.

6.8.12 Costs. The subject of this analysis is techniques and methods of data transmission and as such does not involve equipment or hardware items, except in an implicit way. Therefore, it is not too meaningful to speak of costs except in a relative manner. The major cost items of a given hardware element would be the same regardless of the transmission techniques selected. For example, in the sensors major cost items will be the detection and processing functions, sensor case, packaging, etc., which are independent of the transmission technique. This is also true in the case of repeaters, although perhaps not to the same extent.

6.8.12.1 R&D Costs. Of the alternatives considered, the channelized FD system would undoubtedly entail the least R&D cost necessary to bring it to a production position. This is because of its similarity to the SEAOPSS (DSPG Phase III) sensor communication technique. The SFH system would rank second with regard to R&D costs even though it would be desirable to develop an improved low frequency clock source to obtain the frequency stability required for reasonably fast switching rates (1/10 sec.). Both wideband system types considered would require additional processing gain to overcome their susceptibility to background noise. SWD's with a processing gain of 30 dB or more have been built, but they are expensive and have never been built in production quantities.

The relative rating, with respect to R&D costs, of the system types is summarized in Table II-XII.

TABLE II - XII

COSTS, R&D

Alternative	R&D
	(Note 1) 6/8
A. Narrowband	
1) SFH	1) Some additional R&D required to improve clock sources.
2) FD	2) Probably lowest R&D costs of either system type 8/10
	4/6
B. Wideband	
1) PNSS 2) FFH	R&D costs required to field these system types will likely be higher, assuming additional processing gain will be obtained to reduce peak power requirements.

Note 1. Relative rank of alternatives.

6.8.12.2 Acquisition Costs. This is the cost required to procure and supply an initial system hardware item to the user. There are two major cost categories: a) non-recurring; and b) recurring. As stated previously, there are certain costs which are independent of the transmission technique selected for the DTS; therefore, rather than estimate a total acquisition cost for the DTS, a relative cost comparison will be made between the transmission techniques for each of the major equipment elements in the DTS.

In order to make a meaningful comparison of the cost impact on the DTS of each transmission technique, functional block diagrams of the transmission and receiving elements are given in Figures 2-4 and 2-7. The modulation and transmission functions of each of the transmission types considered in this report are shown in Figures 2-4, 2-5, and 2-6.

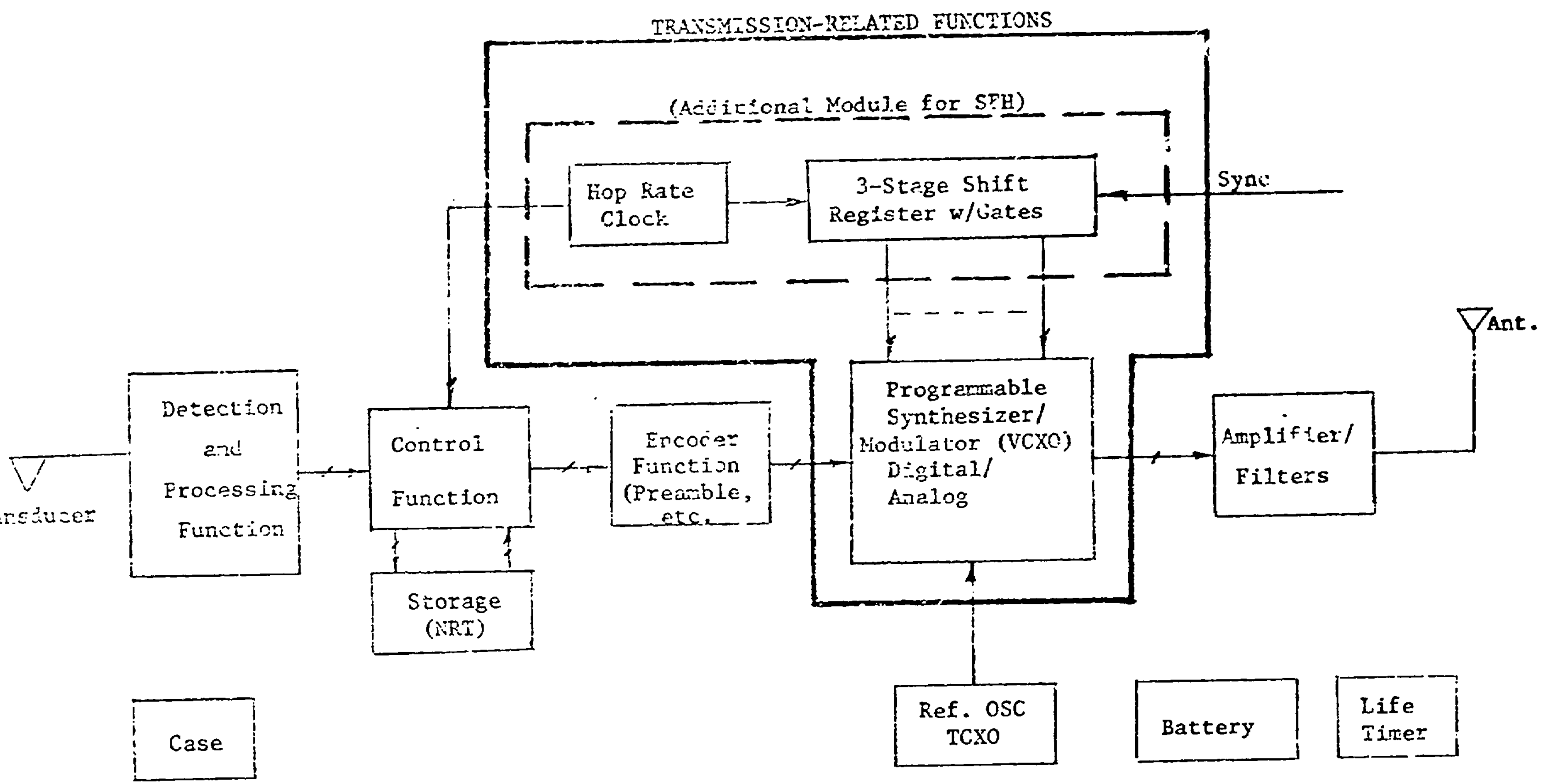
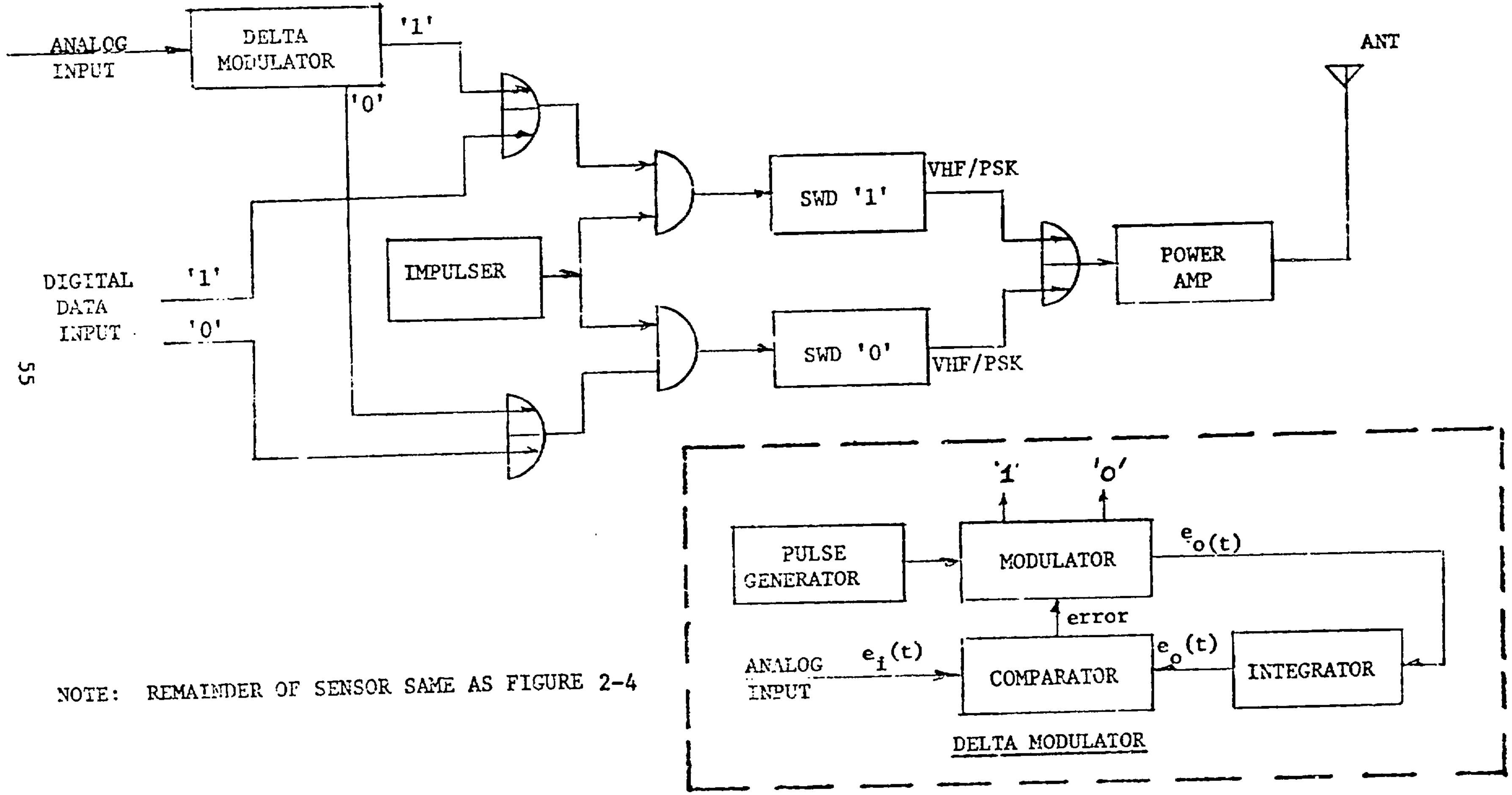


FIGURE 2-4

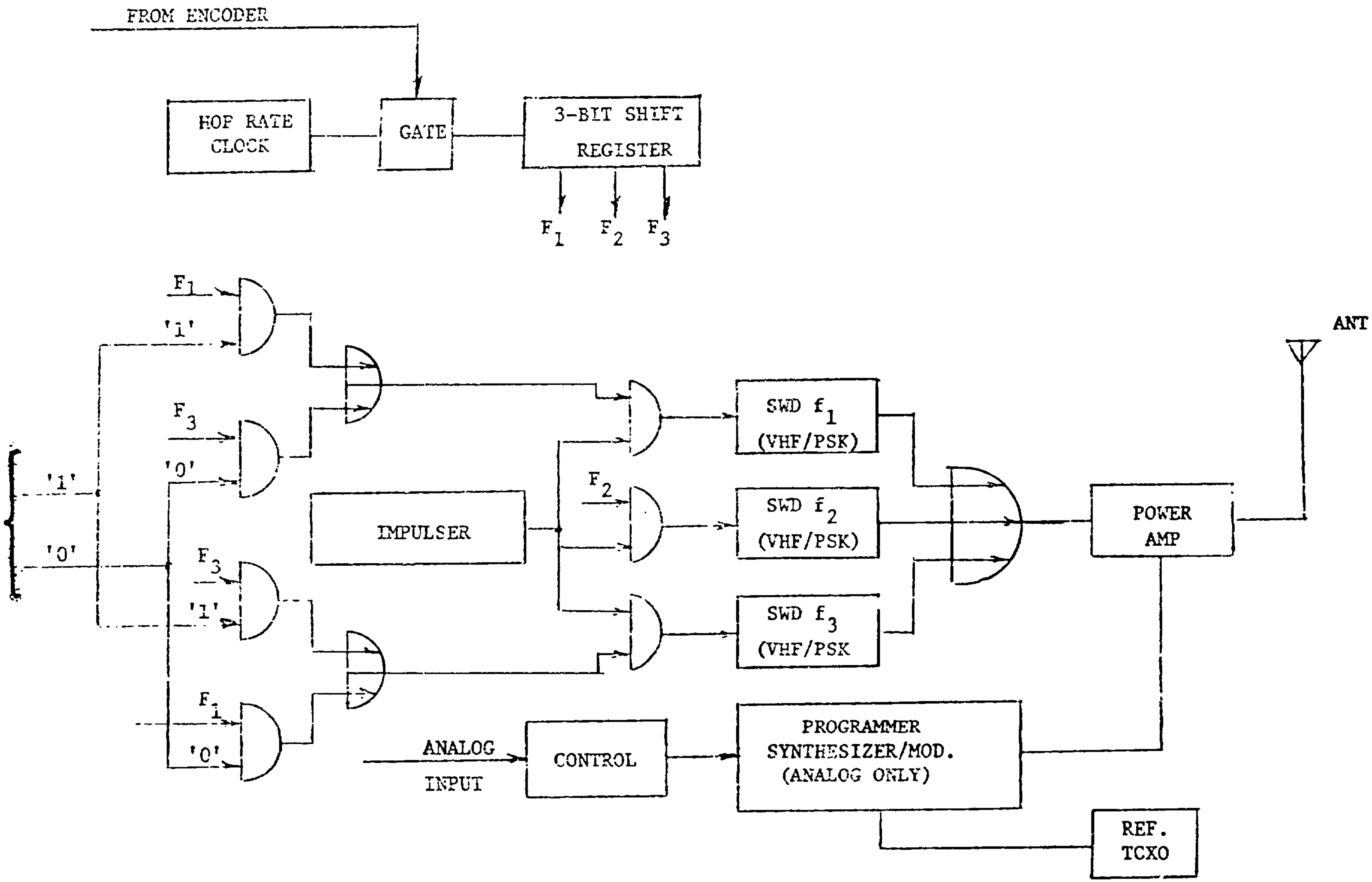
GENERALIZED SENSOR WITH FD AND SFH MODULAR ADDITION
SHOWING FUNCTIONS RELATED TO TRANSMISSION TECHNIQUE



NOTE: REMAINDER OF SENSOR SAME AS FIGURE 2-4

FIGURE 2-5

TRANSMISSION FUNCTION OF PNSS SENSOR W/ANALOG CAPABILITY



NOTE: REMAINDER OF SENSOR SAME AS FIGURE 2-4

FIGURE 2-6. TRANSMISSION FUNCTION OF FFH SENSOR W/ANALOG CAPABILITY

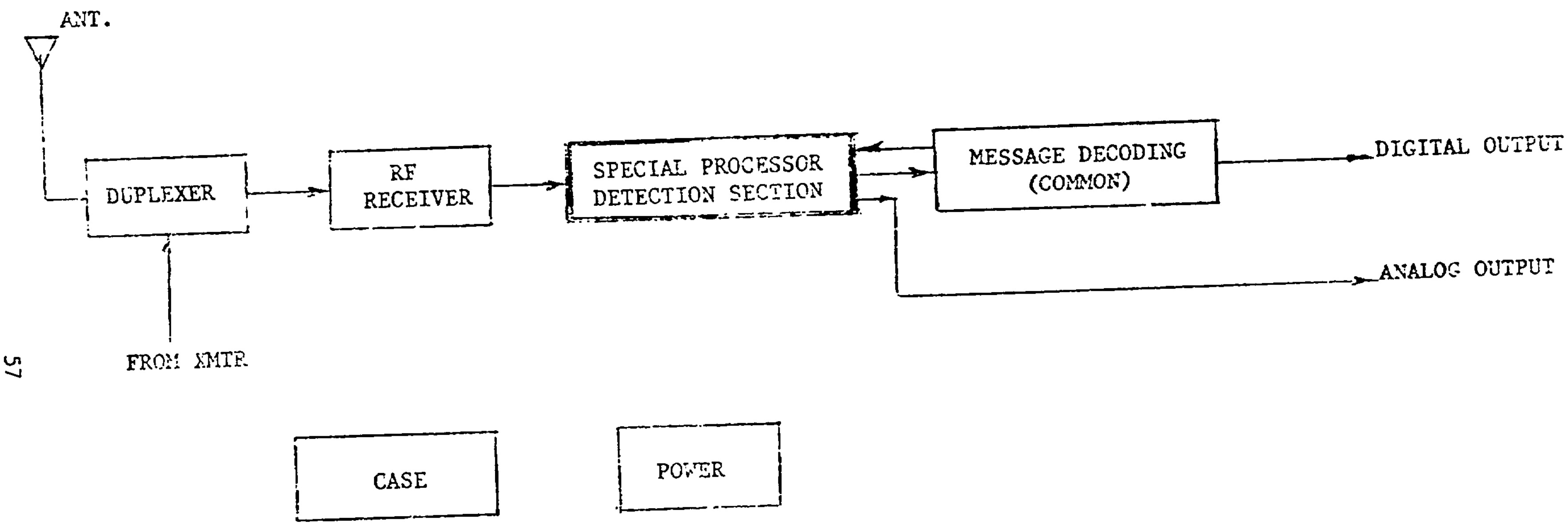


FIGURE 2-7

RECEIVER, SHOWING SECTION UNIQUE TO TYPE OF TRANSMISSION TECHNIQUE

In a similar manner, the detailed receiving functions are shown in Figures 2-8, 2-9, and 2-10. Appropriate parts of these functional units could be combined into a repeater but, since there are several options (e.g., an I.F. Repeater or Baseband Repeater) which one could implement, the impact of a transmission technique on repeater cost can only be inferred from the relative cost differences of transmission and receiving functions.

a) SFH

1) Transmission Function: The SFH transmission technique only requires very little additional functional capability over the FD technique. The additional cost of the Hop Rate Clock depends upon the stability requirements, but is considered to be nominal as compared to the cost of the synthesizer.

2) Receiving Function: As indicated in Figure 2-8, a similar conclusion can be deduced regarding the receiving function of the SFH as compared to the FD.

b) FD

1) Transmission Function: A relative comparison of the FDM technique with both FFH and PNSS requires a distinction between analog and/or digital data transmission requirements. For both analog and digital data transmission, the FD is about one-half as complex as FFH and approximately equivalent to PNSS where analog data is digitized and transmitted in a similar manner as digital data. For digital data transmission only, FD is about equivalent to FFH but slightly more expensive than PNSS.

2) Receiving Function: Similarly, the complexity of the receiving function depends on the type of data being transmitted. This distinction would not have to be made for the UCR since it must be capable of receiving both; however, it is assumed that there will be all-digital repeaters as well as analog/digital repeaters. For digital data reception, the FD technique is more complex than PNSS and about equivalent to FFH. For analog and digital data reception, the FD is about equal to PNSS and about seventy-five percent as expensive as FFH, assuming a synthesizer is used for selecting the channel for analog as is done in the transmitter.

3) PNSS/FFH: (See the discussion of FD for a relative comparison of these techniques). Acquisition cost comparisons are given in Table II-XIII.

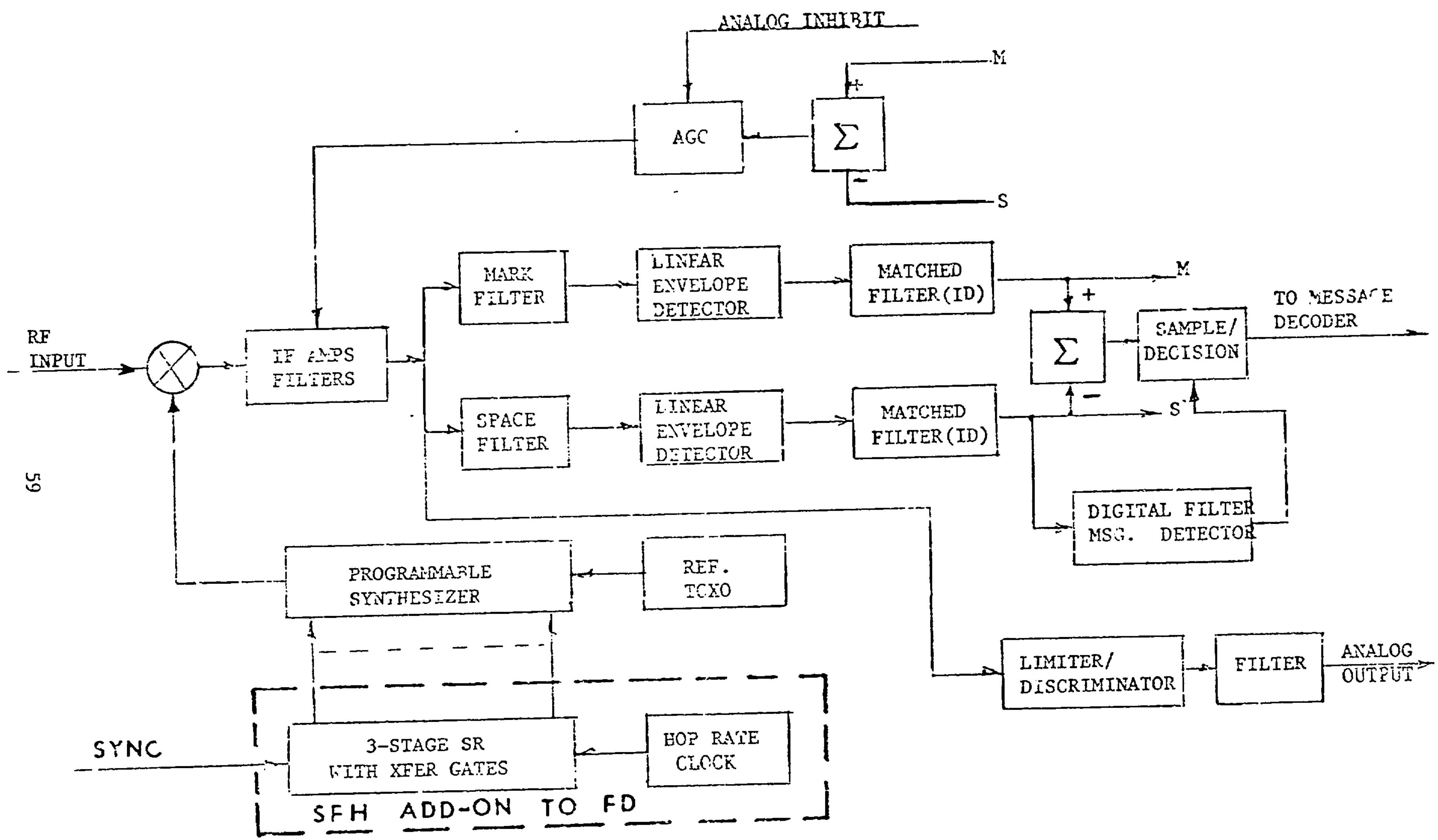


FIGURE 2-8

SIGNAL PROCESSOR/DETECTOR SECTION OF RECEIVER; FD WITH SFH ADD-ON

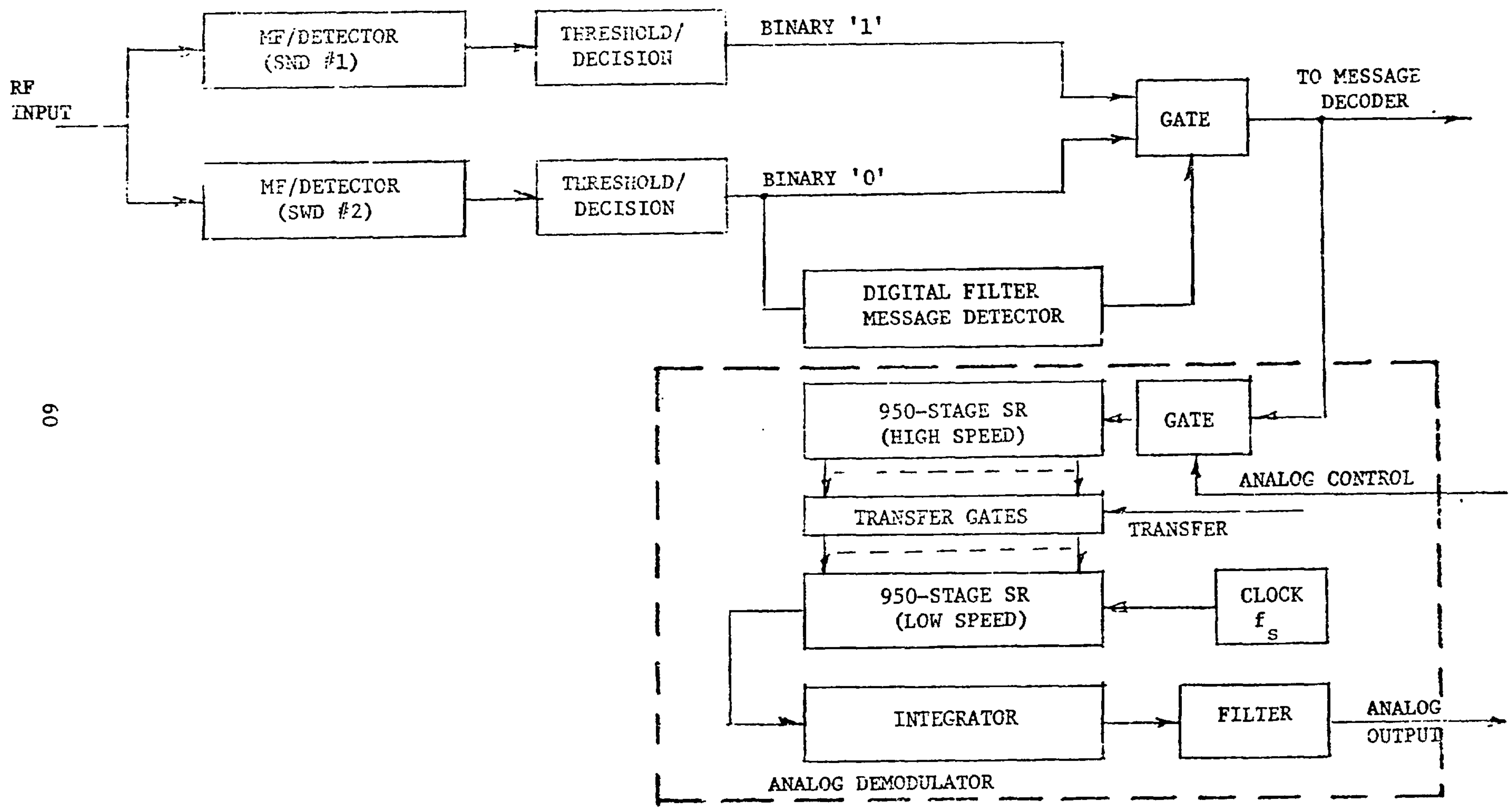


FIGURE 2-9

SIGNAL PROCESSOR/DETECTOR SECTION OF RECEIVER; PNSS TRANSMISSION

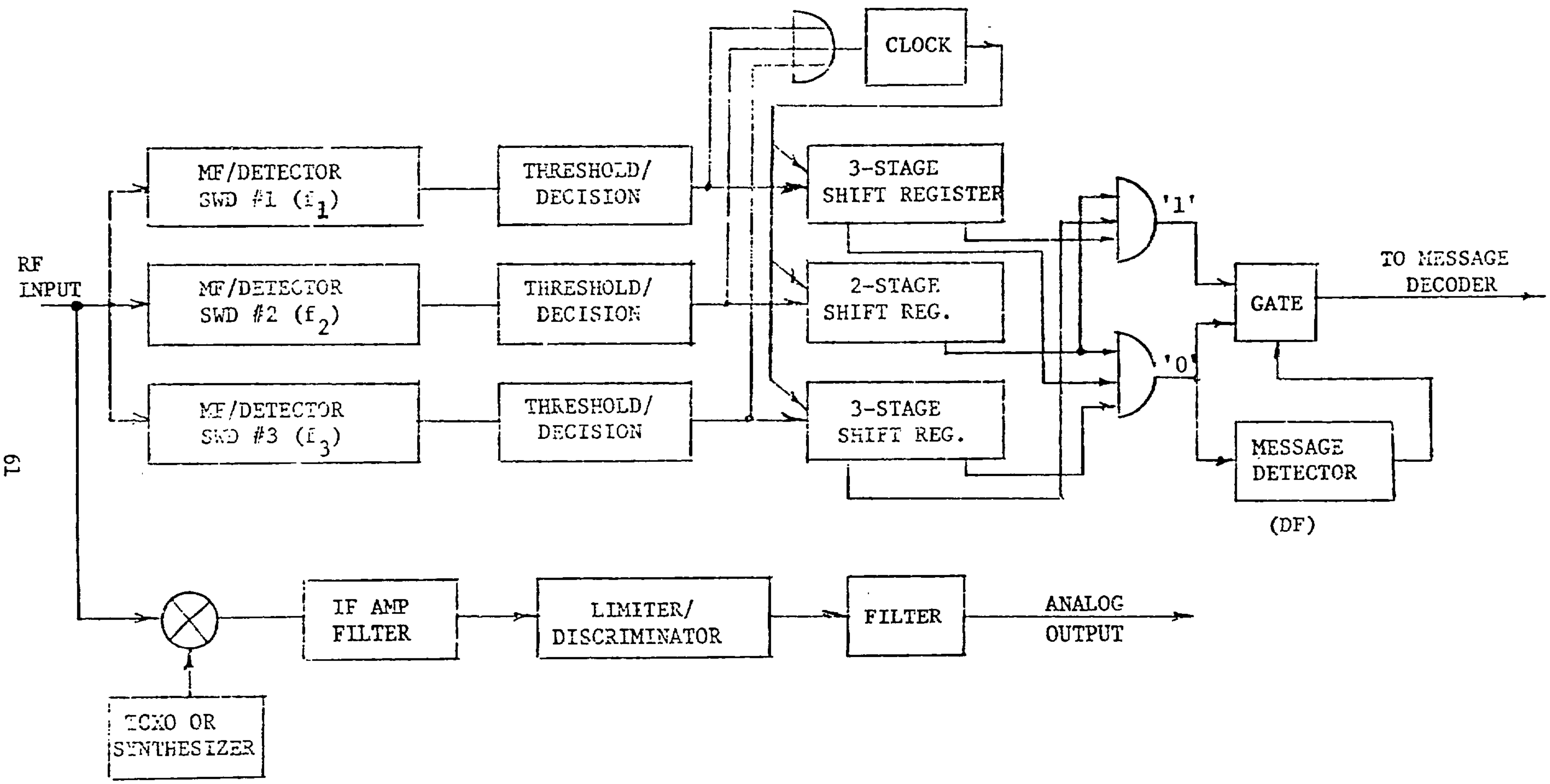


FIGURE 2-10

SIGNAL PROCESSOR/DETECTOR SECTION OF RECEIVER: FFH TRANSMISSION

TABLE II-XIII

COSTS, ACQUISITION

Alternative	Acquisition Costs			
	Transmission Function		Receiving Function	
	Digital Only	Analog & Digital	Digital Only	Analog & Digital
A. NARROWBAND 1. SFH	(Note 1) 6/8 Slightly more expensive than FDM.	6/8 (Same as digital)	6/8 (Same as transmission function)	6/8 (Same as digital).
2. FD	Slightly more expensive than PNSS. About equivalent to FFH. 7/9	Approx. equivalent to PNSS. About 50% as expensive as FFH. 10	About equivalent to FFH. 20%/40% more expensive than PNSS. 7/9	About equivalent to PNSS. 25% less expensive than FFH. 10
B. WIDEBAND 1. PNSS	10 Least expensive of all.	10 Less expensive than FFH and SFH. Equivalent to FD .	10 Least expensive of all.	10 Equal to FD . Less than FFH
2. FFH	(see above) 7/9	(See above) 4/6	(See above) 7/9	(See above) 7/9

Note 1. Relative rank of alternatives.

6.8.12.3 <u>Life Cycle Support Costs</u> (see Table II-XIV). These costs are separated into: a) crew and maintenance personnel; b) replacement; c) integrated logistics support (ILS); d) transportation; and e) depot maintenance.

In a similar manner to the other cost items, these costs will only be considered in a relative way rather than quantitatively.

TABLE II - XIV

COSTS, LIFE CYCLE SUPPORT

Life Cycle Support		
	Personnel (E&M)30	Replacement + 70
	(Note 1)	
A. NARROWBAND 1. SFH	7/9	6/8
2. FD	10	10
B. WIDEBAND 1. PNSS	10	10
2. FFH	10	4/6

Note 1. Relative rank of alternatives.

\+ Replacement includes spare parts

TABLE II - XV

SUMMARY EVALUATION CHART FOR ALTERNATIVES

CRITERION (*) / ALTERNATIVE	COST ( )	PERFORMANCE EFFECTIVE-NESS ( )	VERSATILITY ( )	SCHEDULE ( )	RISK ( )	LOGISTICS ( )	PHYSICAL CHAR. ( )	FINAL RANK
A. NARROWBAND								
(1) SFH	(+) (+)							
(2) FD								
B. WIDEBAND								
(1) PNSS								
(2) FFH								

(*) RANK OF CRITERION IN PARENTHESIS

(+) WEIGHTED SCORE ( ) ( ) WEIGHTED RANK = (WEIGHTED SCORE) X (CRITERION RANK)

7.0 COMPARISON OF ALTERNATIVES (C).

See Addendum A to this engineering analysis.

8.0 SENSITIVITY ANALYSIS (C).

See Addendum A to this engineering analysis.

9.0 CONCLUSIONS

Using a FDM system, the narrowband technique was shown to be clearly superior to wideband when all criteria are properly weighted and averaged. In the area of ECM the wideband technique is preferred, except against broadband jammers. However, it was recognized that no transmission technique is completely and forever immune to a dedicated enemy jamming threat. Therefore, the advantages of a wideband technique in this area did not outweigh its disadvantages in other areas considered.

The results of the evaluation were subjected to a sensitivity analysis to determine the effects of possible incorrect weighting factors or inconclusive ratings against the criteria. The Narrowband EDM Transmission Technique remained the better choice.

10.0 RECOMMENDATIONS

A channelized FDM is recommended. The DTS design should be such that a conversion from the FDM to a narrowband frequency hopping system can be made in the future if the development of this technique materializes to a cost-effective capability. Converting the FDM to narrowband frequency, hopping would provide a measure of protection against jamming not available with FDM.

ADDENDUM A

(CLASSIFIED)

NOT INCLUDED WITH THIS PACKAGE.
CAN BE OBTAINED BY CONTACTING
OFFICE OF THE PM REMBASS.

ADDENDUM B

SENSOR SELF-INTERFERENCE PROBABILITY

ADDENDUM B

SENSOR SELF-INTERFERENCE PROBABILITY

Assume the sensor responses due to target activations follow a Poisson distribution when operating in real time. The probability of getting k responses from a particular sensor in time T, whose average rate of response is λ is given by

1) $$P(k) = \frac{(\lambda T)^k}{k!} \exp - (\lambda T)$$

The probability of simultaneous sensor responses in a field of N sensors may be described by a binomial probability law, where "simultaneous" is defined as responses within a specified time interval. If all N sensors are on the same channel, the probability of simultaneous responses will determine the self-interference probability on the channel.

The probability of exactly t simultaneous responses from N sensors, each with a probability P of responding in the specified interval, (Poisson probability), is given by

2) $$Q\{t;\ N,P\} = \binom{N}{t} P^t (1-P)^{N-t}$$

The probability of t or more simultaneous responses is given by

3) $$Q\{i \geq t;\ N,\ P\} = \sum_{i=t}^{N} \binom{N}{i} P \ (1-P)^{N-i}$$

The probability of self-interference is now determined as follows:
a) given that one of the N sensors has responded to an activation, the probability of a second sensor responding within the specified time interval, Ts, is given by

4) $$Q\{i \geq 1;\ (N-1),\ P\} = \sum_{i=1}^{(N-1)} \binom{N-1}{i} P^i (1-P)^{(N-1-i)}$$
$$= 1 - Q\ \{0;\ (N-1),P\}$$

From 1)

5) $$P = P\ (k \geq 1) = 1 - P\ (k = 0)$$
$$= 1 - \exp - (\lambda Ts)$$

when

$$Ts = \text{"Simultaneous" time interval}$$

Substituting 5 in 4 gives

6) $$Q\ \{i \geq 1;\ (N-1),\ P\} = 1 - \exp - \left[(N-1)\ \lambda Ts\right]$$

If $\lambda Ts \ll 1$ 6 may be approximated by

7) $$Q\ \{i \geq 1;\ (N-1),\ P\} \approx (N-1)\ \lambda Ts$$

The smallest value of Ts for no self-interference would be twice the message duration. However, other constraints may require Ts to be larger than 2 T_m. In particular, for a relay channel where store-and-forward repeaters are used for digital messages Ts must be equal to or greater than 3 T_m in order to insure no ring around problems with repeaters. Therefore, 7 may be

8) $$Q \{i \geq 1; (N-1), P\} \approx 3 \lambda T \quad (N-1)$$

which determines either the message length or maximum number of sensors on a channel given a specified probability of self-interference.

This is equation 7 of Sec. 6.6.1.1.

SECTION III

ENGINEERING ANALYSIS 2 - REPEATER TYPES

1.0 SUMMARY

This analysis addresses the type of repeaters that will be used in the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated against a specific set of criteria; deployment methods, performance, versatility, development/schedule risk, logistics, physical characteristics, and cost. The analysis concluded that the digital only repeater be designed. Judgement on the digital/analog repeater should be based on operational requirements.

2.0 INTRODUCTION

The REMBASS system is composed of several major subsystems. Several different alternative subsystem designs may be found which provide the system operational and functional requirements of REMBASS within certain constraints. In order to determine which subsystem alternative provides the best choice, alternatives are evaluated and analyzed against common criteria and one or more possible alternatives are selected as candidates for final system components. This report is concerned with the selection of the type of radio repeaters that will be used in the DTS.

3.0 STATEMENT OF THE PROBLEM

When the tactical situation or terrain features prohibit direct line-of-sight transmission from sensors to the readout device, radio repeaters will be required to extend the transmission path. This engineering analysis will consider those criteria which impact on the comparison of three alternative repeater types capable of retransmitting either digital data, analog data, or both. The use of In-Band and Out-of-Band techniques to be used for repeaters retransmitting analog data will also be considered. In order to accomplish the REMBASS Material Need (MN) Document requirements, both digital and analog retransmission capability must be included. This capability can be obtained by a DTS using digital or analog repeaters and combined repeaters or a DTS using combined repeaters only.

4.0 ALTERNATIVES

Three alternative types of radio repeaters will be evaluated and analyzed to determine which type best satisfied the REMBASS requirements. These alternatives are: 1) the digital only repeaters; 2) the analog only repeater; and 3) the digital and analog combined repeater.

4.1 Digital Only Repeater. This analysis assumes that the digital only repeater is a narrowband FM/FSK repeater. It is emplaced either by hand or dropped from a fixed wing aircraft or helicopter. It may also be operated from an aerial platform. The digital repeater is capable of relaying both digital sensor data and digital commands. For this analysis only the in-band store and forward (S&F) type repeater is considered for the digital data because it represents the least expensive, and operationally simplest implementation. The digital repeater is a one way reversible, half duplex repeater with one receiver and one transmitter. The term "store and forward" refers to the repeaters operating principle in that the message is received by the repeater, stored in its encoder and then forwarded (retransmitted) by the repeater. Since they alternate, the receive and retransmit functions do not interfere with each other and the receive and retransmit frequencies may be in the same sensor frequency band; in fact they may be identical. Figure 3-1 is a diagram of a S&F digital repeater. The generalized digital repeater described above could employ either narrowband FM/FSK, Slow Frequency Hop (SFH), Fast Frequency Hop (FFH), or pseudonoise spread spectrum transmission techniques.

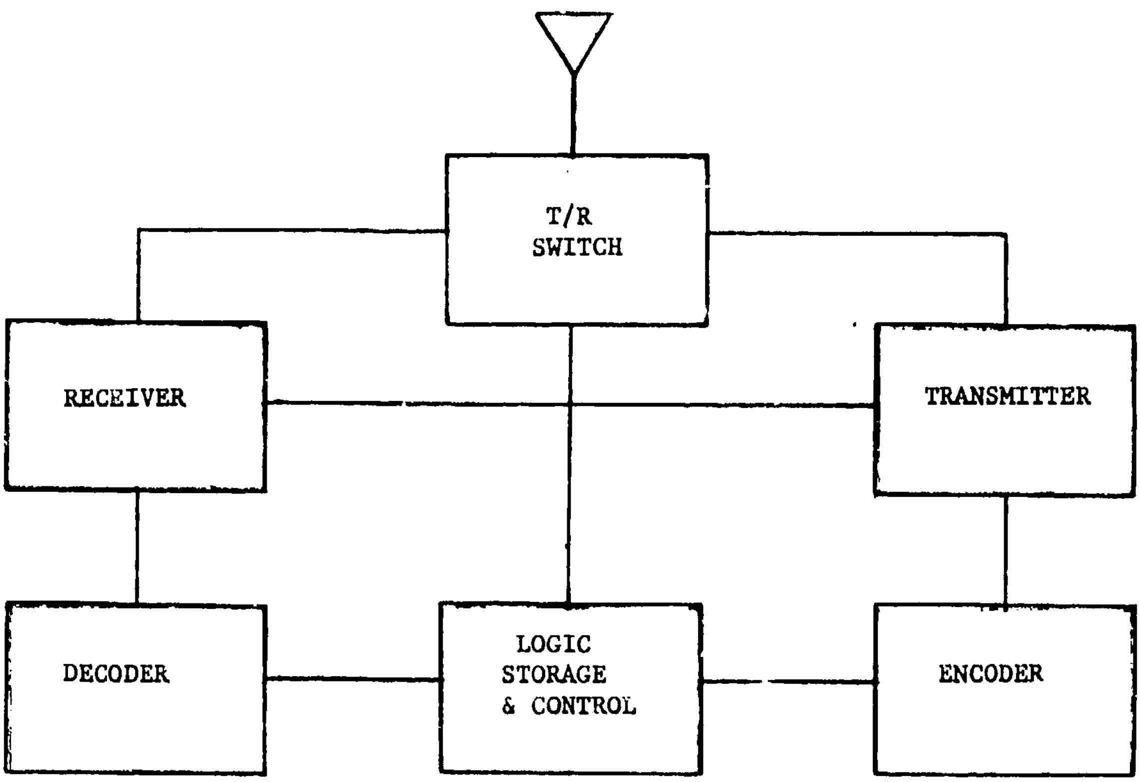


FIGURE 3-1

STORE AND FORWARD DIGITAL ONLY REPEATER

4.2 Analog Only Repeater. This analysis assumes that the analog only repeater is a narrowband FM/FSK repeater. It may be emplaced or operated in the same manner as the digital repeaters. Although not specifically optimized for digital messages, the analog only repeater is capable of relaying analog and digital sensor information and digital commands by treating them as analog signals. The term analog also implies simultaneous real-time retransmission because of the large storage otherwise required. Therefore, the analog only alternative will consider analog only repeaters to have the capability of retransmitting digital sensor information and digital commands but not the capability of decoding the digital data. The most straightforward implementation of a two-way, real-time repeater system is shown in Figure 3-2. It should be noted that the analog only repeater capable of relaying data and command messages, is essentially a dual channel analog repeater.

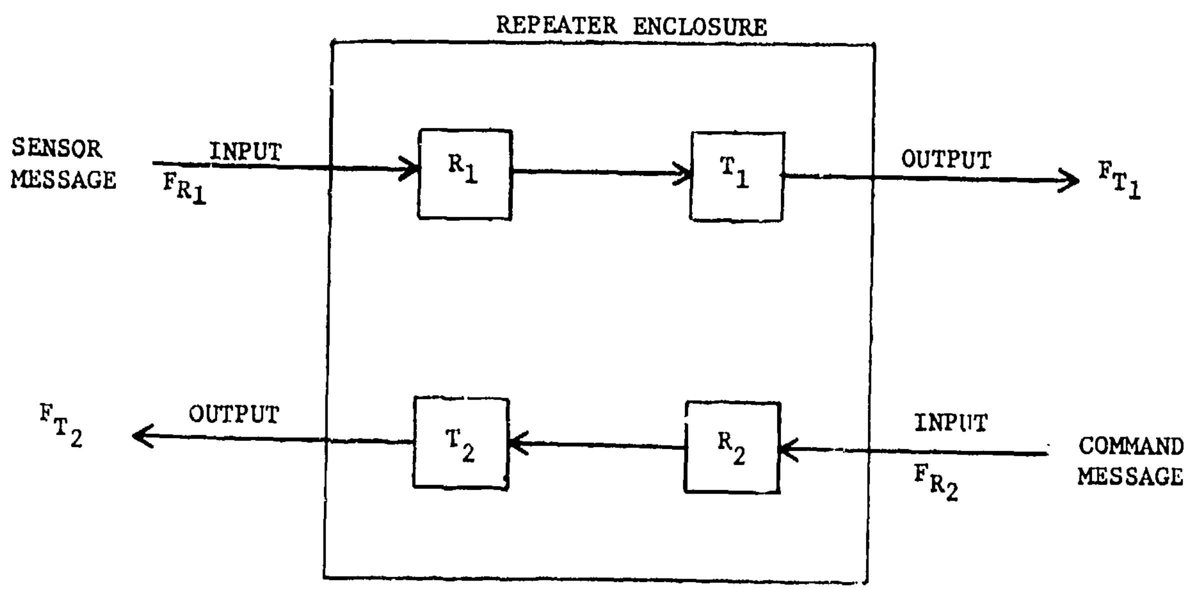


FIGURE 3-2

FULL DUPLEX, REAL TIME ANALOG REPEATER

As shown, the repeater is capable of simultaneous, two-way reception and transmission of two independent signals on different frequencies. One signal would input on frequency F_{R1} and output on F_{T1} while the second signal would input on F_{R2} and output on F_{T2}. The concept is full duplex, requiring two receivers and two transmitters.

4.2.1 Frequency Translation Techniques. Two frequency translation techniques, in-band and out-of-band, are available to the analog repeater to provide F_1-F_2 retransmission. Figure 3-3 shows out-of-band channel separations.

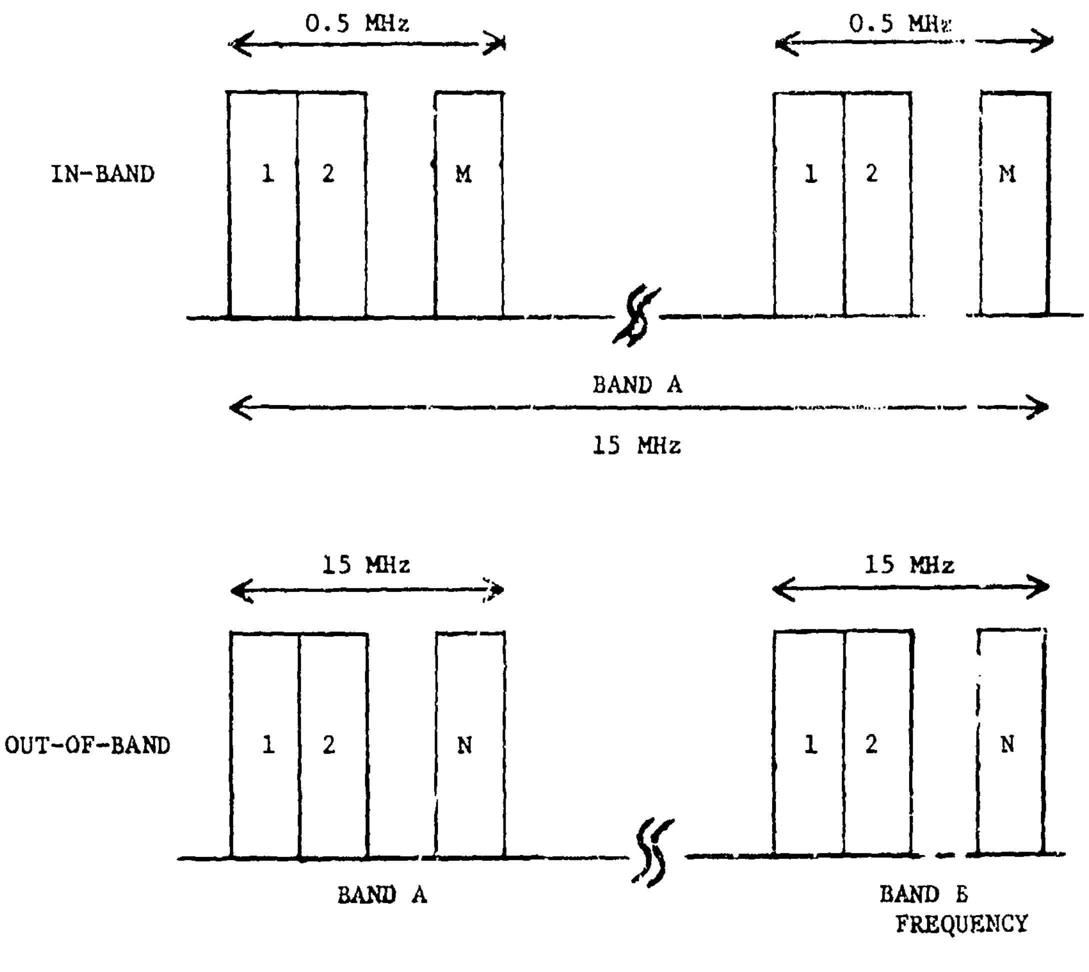


FIGURE 3-3

IN-BAND AND OUT-OF-BAND CHANNEL REPRESENTATION

4.2.1.1 Out-of-Band Technique. Out-of-band frequency translation is a technique in which the reception and retransmission of the sensor message occur on two frequencies which are not in the same contiguous band of frequencies. As a rule of thumb, at least 2:1 separation is desired between F_1 and F_2, (e.g. F_1 = 100 MHz, F_2 = 200 MHz) to keep filter design simple and size small. An out-of-band repeater has need of two frequency bands, and if these bands are separated by more than 15% (15% of the center operating frequency of the lower band) two different receiver and transmitter designs will be required. This is due to the fact that low cost, low power designs of the receiver and transmitter will not permit extremely broad band operation. Some savings may be possible through the use of two different receiver front ends (RF amplifier and local oscillator), one for each frequency band, and utilization of a common function for the remainder of the receiver/decoder. The deployment of the two way simplex multihop out-of-band system is shown in Figure 3-4.

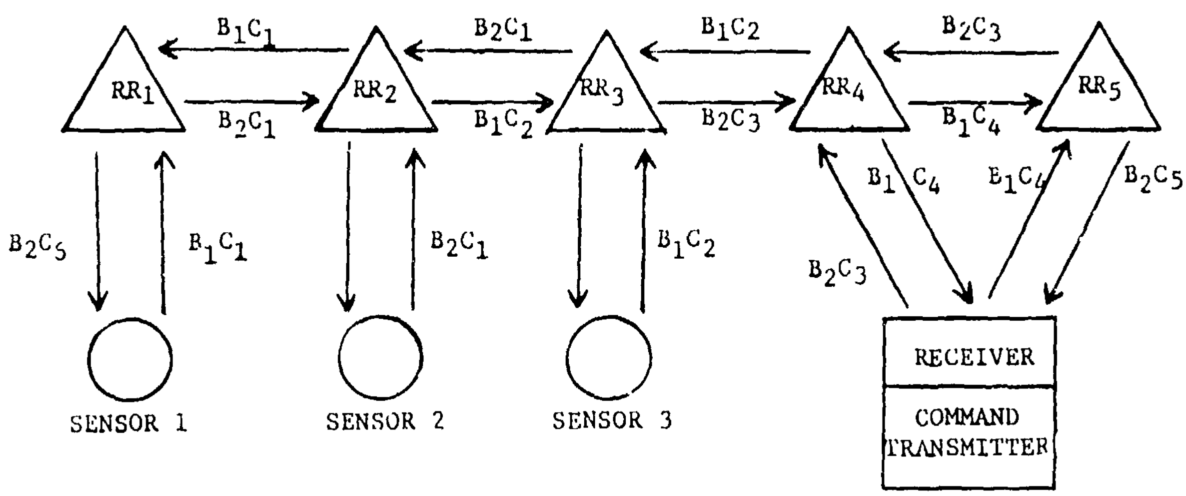
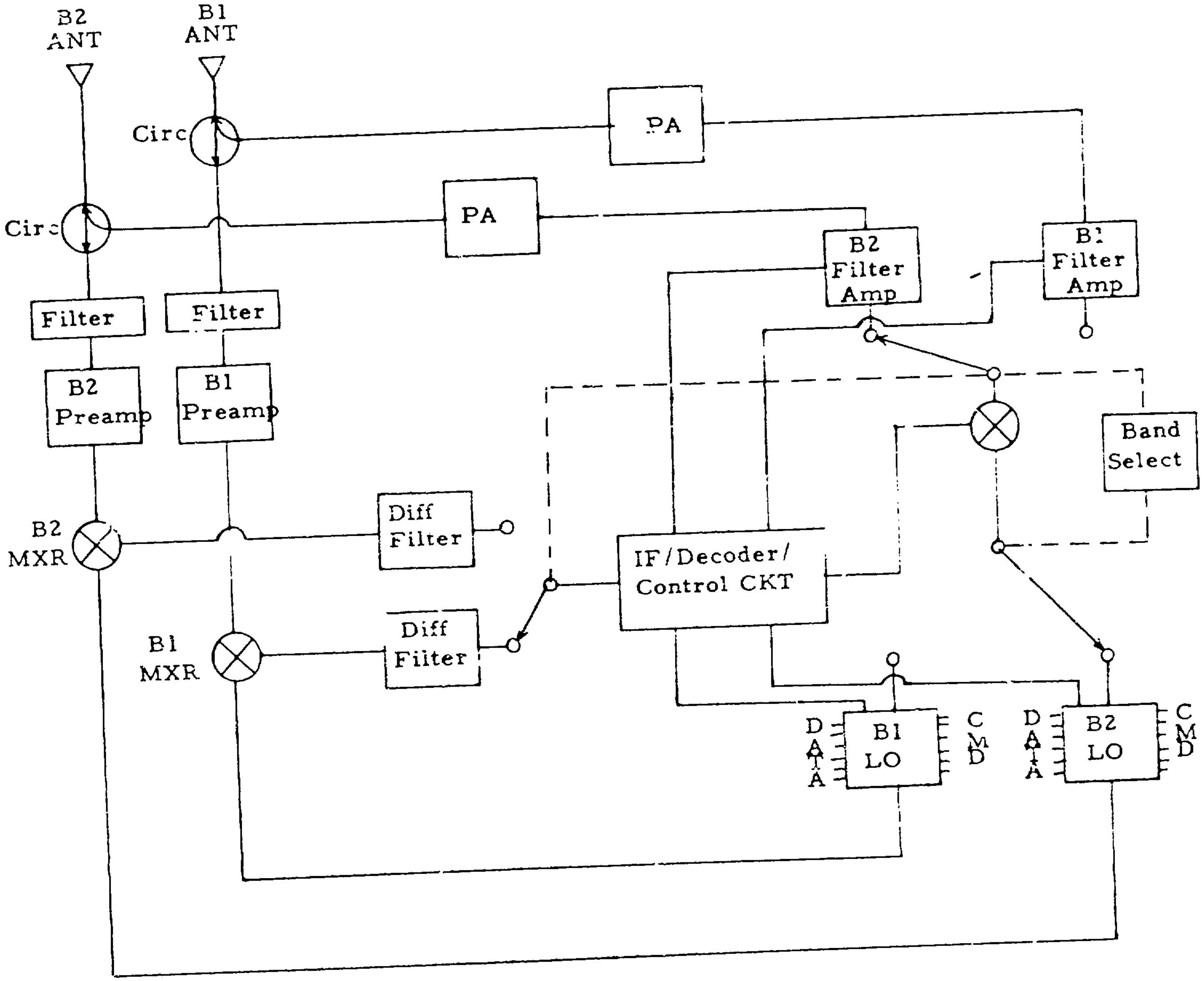


FIGURE 3-4 FIVE HOP OUT-OF-BAND REPEATER SYSTEM

Following a data path, $Sensor_1$ transmits in Band 1 on Channel 1 (written as B_1C_1). RR_1 must necessarily receive on B_1C_1. RR_2 must then receive on B_2C_1, and to prevent spatial ring-around back to RR_1 receiver, transmit on B_1, but now a new channel C_2, must be chosen. This process continues through as many hops as are necessary to complete the link. Sensors are assigned transmit frequencies compatible with the appropriate repeater. Following a command path from the command transmitter to RR_5, it is noted that the command transmitter must transmit on B_1C_4 to be compatible with the RR_5 receiver frequency set by the data path, that RR_5 must transmit on B_2C_3 to be compatible with RR_4 receiver and so on. Note also that Sensor 3 receive frequency must be the same as RR_2, that of Sensor 2 the same as RR_1 and that the receive frequency of Sensor 1 must be assigned a frequency compatible with the command transmit frequency of RR_1. Note that the command transmission band is always the same as the data transmission band, and that only the channel is different; therefore, only a means for separately selecting the command transmission channel must be provided in the repeater. When a command message is transmitted from the command transmitter, it must carry information which tells the RR to transmit on the command channel instead of the data channel. This requires decoding in each repeater rather than straight frequency conversion, a function probably best handled by providing an appropriate preamble to the data and command messages. Upon decoding the information in this preamble, the RR will then enable either the command or data channel. A functional block diagram of a generalized out-of-band repeater capable of multihop and two-way simplex usage is shown in Figure 3-5. Assume a signal is received in Band 1. It is passed through appropriate preamplification and mixed with the Band 1 local oscillator (LO) to form an IF. This signal is decoded, looking for preamble instructions to switch the Band 2 LO to the preset command frequency for retransmission. If no such instruction is received, the Band 2 LO remains at the data frequency and sums with the IF to form a Band 2 signal which is then filtered and amplified to the full transmitter power. If the preamble had indicated a command transmission would follow, the control circuitry would have switched the Band 2 LO to its preset command frequency.

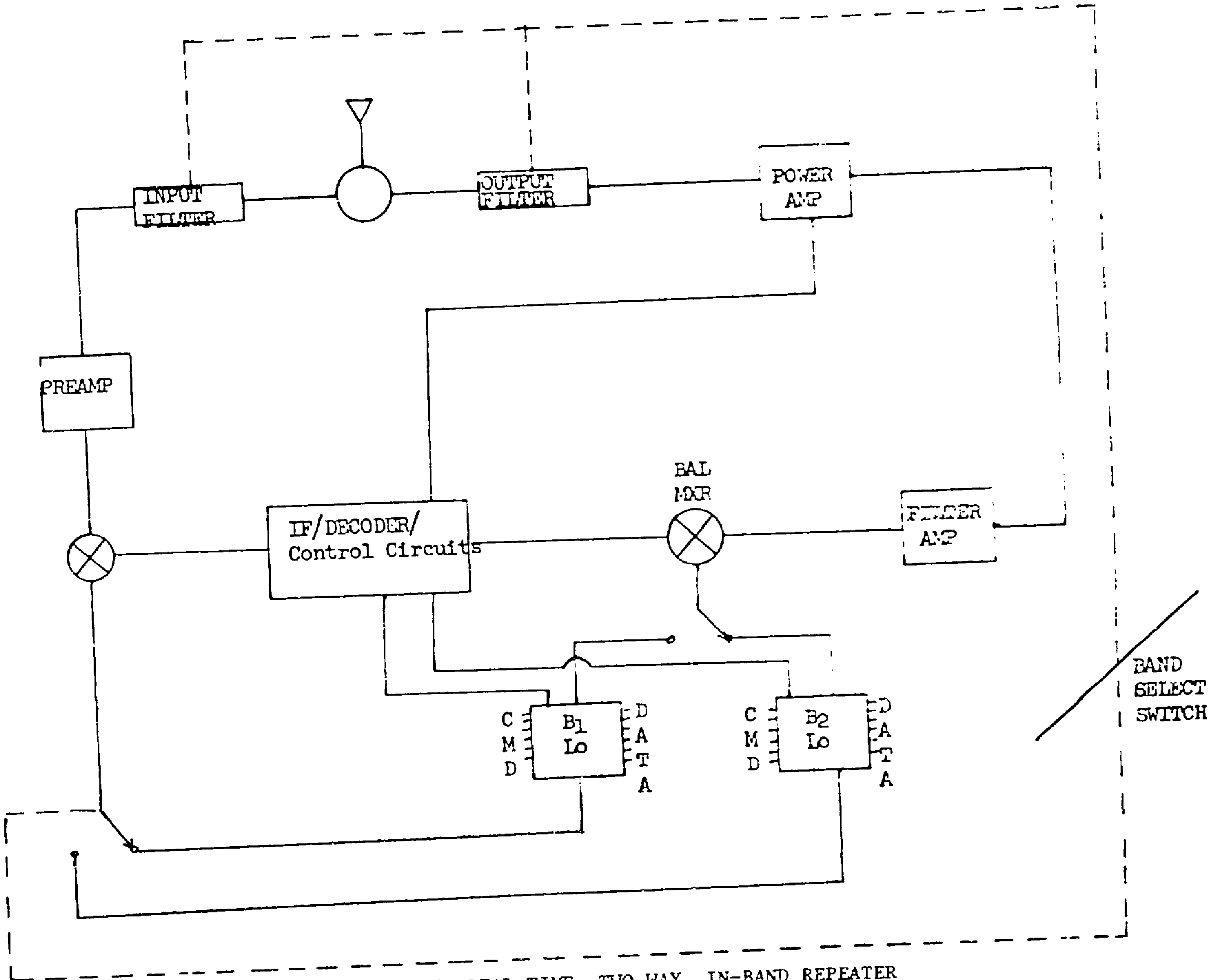
A manual band select switch provides two band operation; if a signal is received in Band 2, operation of the repeater is unchanged from above except that the Band 1 and Band 2 LO actions are reversed.



REAL TIME, TWO WAY, OUT-OF-BAND REPEATER

FIGURE 3-5

4.2.1.2. In-Band Technique. In-band frequency translation is a technique in which the reception and retransmission of the message occurs on two frequencies which are located within a contiguous band of sensor frequencies. Simultaneous reception and retransmission occur on receive and transmit frequencies which are separated anywhere from 100 kHz to 12 MHz within the sensor frequency band. An in-band repeater presents a difficult design problem to achieve the isolation (filtering) required to avoid interference between the simultaneous receive and retransmit operations within a 12 MHz frequency band. The isolation can be achieved through the use of physically large and relatively expensive RF filters, or through the use of sophisticated adaptive cancellation techniques. A functional block diagram of such a repeater using filters is shown in Figure 3-6. Assuming a signal is received in Band 1, it passes through the input filter which functions as a preselector reducing the occurrence of spurious/image responses and intermodulation products in the preamplifier due to transmitter energy. The B1 LO (either fixed or tunable) mixes with the incoming signal to provide the IF which, upon preamble decoding, tells the repeater whether or not to switch to the preset command channel for transmission. If no channel switch is indicated, the B2 LO remains at the data frequency and mixes with the IF to produce the desired Band 2 transmit signal. The signal is then filtered to eliminate out-of-band mixer outputs and amplified as necessary to provide the desired output level. This amplified signal is then passed through the output filter which acts to reduce transmitter output energy in the receive band more than 80db. This rejection plus the signal-to-noise ratio at the transmitter output provides the necessary isolation. If the received signal were at F_t instead of F_r, repeater operation would be identical except that the LO's and the input and output filters would reverse functions.



FIGURF 3-6 REAL TIME, TWO WAY, IN-BAND REPEATER

4.? Digital and Analog Combined Repeater. A digital and analog combined repeater is a single RF channel narrowband unit that receives on one frequency and transmits on a different frequency. It is deployed either by hand emplacement, air dropped, or operated from an aerial platform. The combined repeater is capable of relaying analog and digital sensor information and digital commands. The combined repeater contains a digital decoder which permits it to decode and recognize the digital sensor and command messages and also the digital header portion of the analog sensor message. It must be capable of retransmitting the message in the correct direction (i.e. on the correct frequency) if a frequency translation is involved. Only one receiver would be required for the repeater. Transmission of the message could be accomplished by using two transmitters or one transmitter with a digital frequency synthesizer capable of switching between the two required transmit frequencies. The concept of using one receiver to relay command and sensor messages can be considered a simplex operation. Simplex operation also permits design of hardware within the life and size restrictions of ground use. Specifically, time sharing a single receiver and transmitter: a) doubles battery life projections through the elimination of one receiver; b) reduces the overall size through the elimination of one receiver and one transmitter; and c) improves reliability through reduction of parts. In a real-time relay system, the receive and transmit functions are simultaneous and isolation is achieved with filtering made possible by appropriate separation of the receive and transmit frequencies, F_R and F_T. A typical real time simplex analog system with five hops is depicted in Figure 3-7.

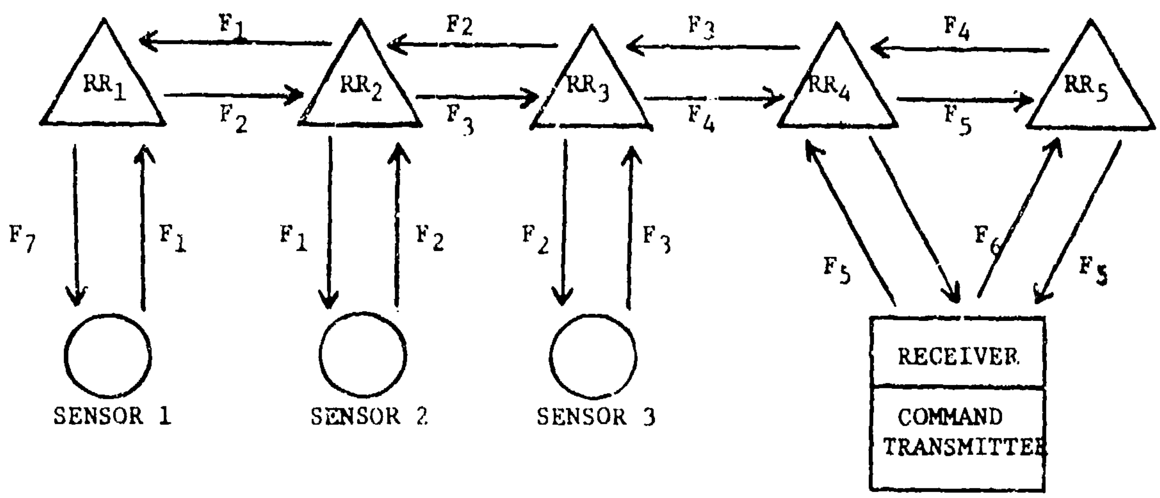


FIGURE 3-7

REAL TIME MULTIHOP RELAY SYSTEM (REMURS)

Following a data path from $Sensor_1$, transmitting on F_1, RR_1 must necessarily receive on F_1. To achieve isolation. RR_1 transmits on F2. RR_2 must receive on F_2, and to prevent spatial ring-around back to RR_1 receiver, transmit on F_3. This process continues through as many hops as are necessary to complete the link. Sensors are assigned transmit frequencies compatible with the appropriate repeater. Following a command path from the command transmitter to RR_5, it is noted that the command transmitter must transmit on F_5 to be compatible with RR_5 receiver frequency set by the data path, that RR_5 must transmit on F_4 to be compatible with RR_4 receiver and so on. Note also that $Sensor_3$ receive frequency must be the same as RR_2, that of $Sensor_2$ the same as RR_1 and that the receive frequency of $Sensor_1$ must be assigned a frequency compatible with the command transmit frequency of RR_1.

5.0 CRITERIA

The criteria which will be used in the comparative evaluation of the alternatives associated with this engineering analysis are defined in this section. In Section 6.0 each alternative is evaluated against these criteria. Then each alternative is ranked against other alternatives for each criterion and a relative ranking is presented for each major criterion. The data will be used in Section 7.0 to make a comparative analysis of the alternatives to determine which most nearly meets the REMBASS requirements.

5.1 Deployment Methods. The REMBASS MN requires that repeaters be emplaced by various means and that they also be capable of being installed and operated from an airborne platform. How these requirements impact the design, construction, etc., of the various alternatives will be considered.

5.1.1 Hand Emplacement. This is a method of deployment which requires foot troops to carry the repeater to the desired installation location. Size, shape, and especially weight are critical factors for this criterion.

5.1.2 Air Drop Emplacement. This method implies that the repeater may be emplaced from a fixed wing or rotary wing aircraft. The repeater may be dispensed by hand, from a SUU-42 type dispenser or from special bomb racks such as the PMBR.

5.1.3 Airborne Platform. In this method of deployment the repeater may be securely fastened inside the aircraft with its antenna attached in some convenient position outside the aircraft. The major factors influencing the repeater selected for this method of operation are shock and vibration resistance, and RF interference.

5.2 Performance. Each of the alternatives will be evaluated against specified performance parameters.

5.2.1 RF Isolation. A repeater operating in real-time requires that the transmitter output be isolated from the receiver input to prevent feedback causing signal distortion. In a multihop relay chain, feedback may also occur from consecutive repeaters if special precautions are not taken to prevent it, such as frequency offset between repeaters.

5.2.2 Message Delay. This relates to the fact that a repeater operating in a non-real-time mode will cause a time delay between message receipt and retransmission. This is characteristic of S&F repeaters.

5.2.3 Message Loss. This criteria evaluates the probability of losing a message through the repeater because of self-interference, errors, etc.

5.2.4 (S/N) Degradation. The quality of an analog signal will be degraded by a reduction in the signal-to-noise ratio as it is received and transmitted through an analog repeater. Digitized analog data may be transmitted through digital repeaters with only minor loss of quality due to the reconstitution of the digital signal at each repeater.

5.2.5 ECM Vulnerability. This is a measure of the vulnerability of a particular type of repeater to a jamming or countermeasure environment.

5.2.6 Antenna Requirements. The repeater alternatives to be considered may require dual antennas that operate in widely differing frequency ranges, especially if out-of-band repeaters are considered.

5.2.7 Spectrum Utilization. This criteria relates to the effectiveness with which a particular alternative uses the assigned frequency band. It is related to the number of relay links which are available, and how frequencies must be assigned to repeaters.

5.2.8 Energy Requirements. Since the repeaters will generally be required to operate from batteries, the amount of power and energy required is a significant criterion for evaluating alternatives. Standby power and energy per message are measures of comparison.

5.3 Versatility. This is the ability of a repeater to relay both digital and analog messages.

5.4 Development Schedule/Risk. Schedule and risk are related criteria and determine the extent of development required and the probability of successfully acquiring a particular repeater alternative.

5.5 Logistics. The logistics aspect of each alternative is evaluated in terms of the maintenance skills, repair parts, and special test equipment required.

5.5.1 Test Equipment. The special equipment needed to properly support a given repeater in the field.

5.5.2 Repair Parts. The number of unique components necessary to support a repeater in the field in case of failure or malfunction.

5.5.3 Maintenance Skills. The special technical skills required of support personnel in the field.

5.5.4 Equipment Adjustments. The number of adjustments required during operation.

5.6 Physical Characteristics.

5.6.1 Volume. Along with size, the volume of the repeater may determine its ability to be used in certain air dispensers.

5.7 Costs. Costs for each alternative are estimated to include all costs from engineering development, initial purchase and supply of each Army element with the required system components, to the continued resupply of equipments with supporting costs for the expected life cycle of the system.

5.7.1 R&D Costs. This is the cost required to develop and test the device to the point where initial production may begin. Extending the state-of-the-art of a required capability may be required in some cases.

5.7.2 Acquisition Costs. This is the cost required to procure and stock the required Army elements (division, battalion, etc.) with the equipment, spare parts, software, etc., for an initial operational capability. Subsequent costs are covered under life cycle support costs.

5.7.3 Life Cycle Support Costs. These costs are required for replacement items, support personnel, management, transportation and depot maintenance.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 General. The MN specifies that repeaters will be required to extend the transmission path when the tactical situation or terrain features prohibit direct path sensor to read-out device (UCR/T or SRU) transmission. It also requires that the DTS be capable of sending both analog and digital data. This technical evaluation will consider those criteria which impact on the three alternatives of building digital only, analog only, or combined relays and the techniques to be used for analog repeaters. A substantial portion of this analysis has been previously presented in Feb. 1973 to the ODDR&E Sensor Frequency Coordination Committee in a CSTA Laboratory report entitled "The Sensor Radio Relay."

6.2 Criteria Evaluation.

6.2.1 Deployment Methods. The REMBASS MN states that the repeater must be capable of being hand-emplaced, air-dropped, or operated from an airborne platform The evaluation of the separate repeater types against these criterion will be mostly concerned with the physical criteria which is addressed in a separate section of this report.

6.2.1.1 Hand Emplacement. The problems inherent in the design and fabrication of a repeater capable of withstanding normal storage and hand emplacement by troops appears to present no major problem. Volume will be the most significant criteria in evaluating the practicality of a hand emplaced repeater.

6.2.1.2 Air Drop Emplacement. For air emplacement, volume, configuration, electronic and structural design,and fabrication considerations become paramount. Several air dropped sensors have been developed and results of live tests of these sensors indicate fair survivability performance with failures due primarily to connectors and crystals. The hardware experience obtained through these developments are directly applicable to air-dropped repeaters; however, emplacement accuracy and antenna height requirements for repeaters are considerably more demanding than for sensors.

6.2.1.3 Airborne Platform Operation. The REMBASS radio repeater may be required to operate in an aerial platform, such as a rotary or fixed wing aircraft. With proper design it is anticipated that a standard hand emplaced repeater will fulfill the airborne requirement. Therefore, in designing and fabricating the hand emplaced repeater consideration will be given to the additional shielding required for the aircraft system EMI compatibility, and aircraft vibration and shock characteristics.

Because of the broad geographical area of coverage afforded by an airborne repeater, the potential for interference from ground based repeaters or sensors on common or adjacent channels is significantly higher than between ground based repeaters. Consideration must therefore be given to selecting transmission and frequency translation techniques which afford a sufficient channel capacity to enable assignment of the required number of sensor and repeater channels, and which provide a low interference potential.

6.2.2. Performance.

6.2.2.1 RF Isolation. The basic problem in the design and fabrication in any repeater system is RF isolation between its output and input. Sufficient isolation between the receiver and transmitter must be maintained in order to prevent the repeater transmitter from activating or desensitizing its receiver via either internal or external feedback paths, a situation known as "Ring-Around" (Figure 3-8). A variation of ring-around is experienced in multihop usage in that a repeater transmitter must not activate its own receiver or any previous repeater receiver in the hop chain. This latter situation is known as spatial ring-around and is shown in Figure 3-9.

6.2.2.1.1 Digital Only Repeater. As stated in 6.2.1, the digital repeater employs S&F technique. The S&F technique eliminates single repeater ring-around (Figure 3-8) regardless of whether F1 - F1 or F1 - F2 frequency translation is employed. However, spatial ring-around could still occur in multihop operation in an F1 - F2 system or if any of the F1 - F2 frequencies are reused (as a result of limited number of frequencies or poor frequency management) within the range of RF propagation. Transmissions from other repeaters, sensors, SCM's, and command transmitters operating on the same or adjacent RF channels, if close enough to be repeaters in question, will be received by the repeater. Thus, reception of messages not intended to be retransmitted by a particular repeater is possible. However, by adding a repeater address to the message or by storing the message ID, the repeater in question can determine if it has previously transmitted the same message or is attempting to relay a message from another sensor field (i.e. it can identify invalid messages). In summary, the decoding logic in the digital repeater must be designed to eliminate retransmissions of previously transmitted messages to eliminate spatial ring around.

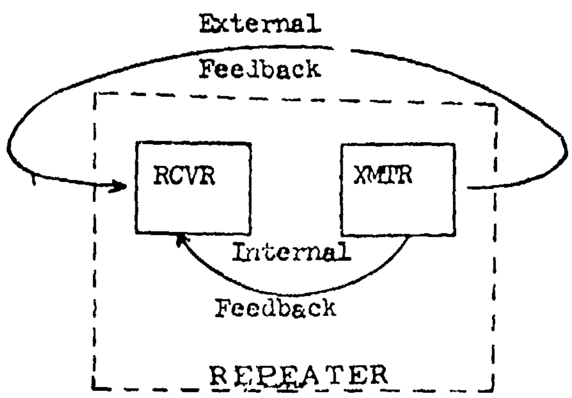


FIGURE 3-8 RING-AROUND

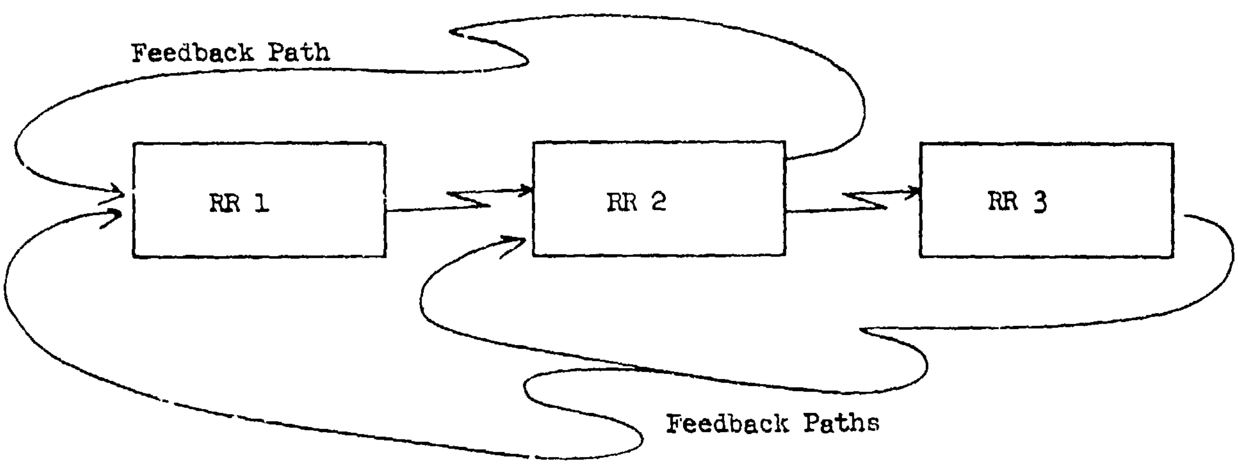


FIGURE 3-9 SPATIAL RING-AROUND

6.2.2.1.2 Analog Only Repeater. The analog only repeater operates in the F1 - F2 frequency translation mode (either in-band or out-of-band) and the receive and retransmit functions occur simultaneously. No decoding logic will be incorporated in the analog only repeater to discriminate between valid messages and invalid messages from adjacent sensor systems operating on the same RF channel. The analog only repeater will require strict frequency management to prevent retransmission of invalid messages.

6.2.2.1.3 Digital and Analog Combined Repeater. The digital and analog combined repeater can only operate in F1 - F2 frequency translation mode but contains decoding logic which will allow it to recognize and retransmit only valid messages and commands. It has the same invalid message rejection capability as the digital only F1 - F2 repeater.

In summary, the combined repeater is capable of rejecting invalid messages; however, strict RF frequency management is required to avoid message loss due to interference from messages transmitted on reused RF channels. Table III-I indicates the relative ring-around performance of three repeater alternatives.

TABLE III-I

RF ISOLATION RATINGS

ALTERNATIVE	COMMENT	RATING
ANALOG	Requires strict frequency management and more channels.	5
DIGITAL	Minimum frequency problems. Requires Repeater ID.	10
COMBINED	Requires some frequency management. Requires Repeater ID.	8

6.2.2.2 Repeater Message Delay and Loss. Sensor and command messages may experience delays in being retransmitted in either single or multihop systems depending on the type of repeater employed. In addition, the type of repeater will also effect the loss of messages or portions of the information being retransmitted through the system.

6.2.2.2.1 Store and Forward Digital Only Repeater. The S&F digital repeater approach in a multihop system with n repeaters results in message delays equal to n times the basic message length. This is due to the fact that the message is completely received and stored prior to retransmission. The S&F digital repeater greatly increases the statistical probability of message loss due to message overlap in comparison to real time repeater operation. *This is due to the fact that the receiver in the repeater is turned off while the message is being retransmitted and a finite probability exists that other sensors might transmit a message while the receiver is turned off.

6.2.2.2.2. Analog Repeater. Analog only repeaters retransmit messages in real-time and the propagation delay accounts for the majority of delay time in relaying the message to UCR/T. Although little or no time loss is experienced in relaying the message, analog repeaters still have a basic statistical loss due to message overlap. The probability of message loss due to overlap increases greatly for analog messages because the analog messages are hundreds of times longer than the digital message. However, calculation of the actual loss of messages, particularly where analog and digital messages are intermixed, requires very judicious choice of parameters and interpretation of the probability of message loss equation to obtain meaningful results.

6.2.2.2.3 Combined Repeater. The digital and analog combined repeater retransmits a message after the digital header portion of the message (Preamble, Message Type, ID's etc) has been decoded, checked, and reinserted for modulation of the transmitter. A small portion of the analog information (1 header length or .50msec) following the digital header is cut off at each radio repeater to allow for reinsertion of the new header. Up to 1/4 sec will be removed from the analog portion of a message in passing through a 5 hop repeater chain. The digital portion of the message is actually being processed in a S&F mode while the analog is real time. See Figure 3-10.

*Sensor transmissions may occur in a near simultaneous time frame and compete with each other in attempting to be relayed back to the UCR/T. A statistical model using the Poisson distribution is a method of predicting the probability of a message being lost due to competing sensor transmissions (Alternatively it also represents the percentage of message lost). Prob of message loss = 1 exp $[-K(N-1)\lambda T]$

where K = factor of values 1 to 3, determined by system

N = number of sensors in field

λ = average sensor activation rate

T = message duration

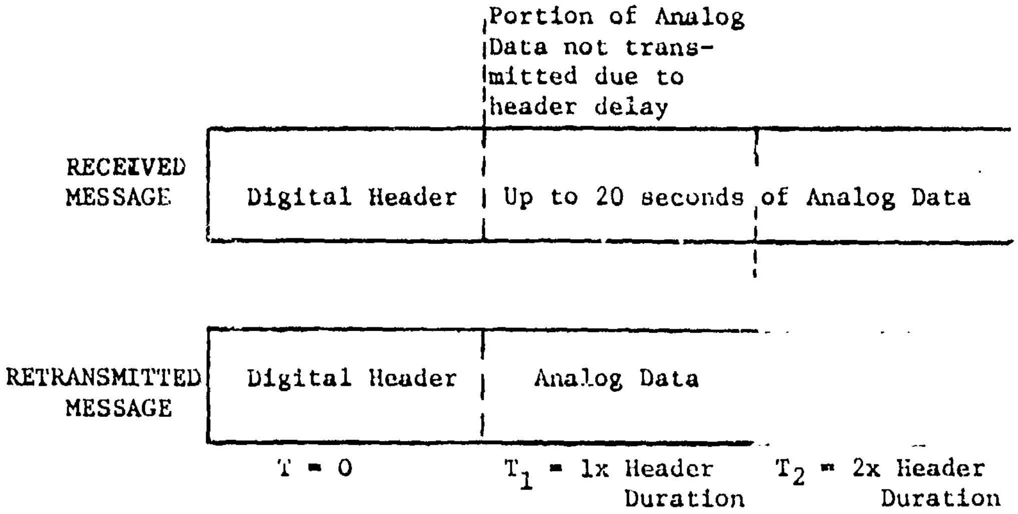


FIGURE 3-10

PICTORAL REPRESENTATION OF ANALOG LOSS DUE TO HEADER DELAY IN COMBINED REPEATER

While a portion of the analog message is lost at each hop, the amount is negligible and of little consequence in sensor applications. Example: For an assumed header of 50 millisecond duration and 20 seconds of analog data the loss for a single repeater represents 1/4 of one percent of original analog information. For a five hop system the loss would be 1-1/4% of the original analog information. The probability of message loss for the combined repeater is equal to that of the S&F digital repeater when retransmitting digital messages and equal to the analog only repeater when retransmitting analog messages. Table III-II indicates the message delay and message loss performance of the three types of repeaters.

6.2.2.3 <u>Signal to Noise Degradation - Digital vs Analog</u>. Analog and also combined repeaters retransmitting analog data can be considered as band limited amplifiers which amplify both input signal and in band noise, while adding a little noise of its own. Consequently the signal-to-noise (S/N) ratio progressively decreases with each repeater so that after a system consisting of M links, the final (S/N) is:

$$\left(\frac{S}{N}\right)_M = \frac{1}{M} \times \left(\frac{S}{N}\right)_{1st\ relay}$$

For example, assume that a sensor transmission is to be retransmitted by 5 repeaters of equal characteristics (e.g., output power, sensitivity, link distance, etc.) to a UCR/T - assume also that the (S/N) in the IF of the first repeater ranges over 10-12-17dB. Using the above relation it is determined that available (S/N) at the UCR/T is reduced to the respective range of 3-5-10dB. Another way of expressing the degradation in (S/N) in passing through a M hop link is (S/N) (dB) - 10 log M, where (S/N) is the signal-to-noise ratio in the IF amplifiers of the first repeater. For M = 5 the loss is 7dB. Therefore, in a system of repeaters retransmitting analog data, (S/N) at the UCR/T is considerably reduced. For fixed transmitter power, the reduction in (S/N) caused by the analog repeaters implies that the repeaters must be deployed closer together in order to maintain a reliable communications link (i.e., the more repeaters in the system, the shorter the operating range of each repeater). A digital S&F repeater however is a regenerative repeater in that the data is converted to baseband, decoded, stripped of most of its noise and then retransmitted. The overall error rate of the multihop link will obviously increase as the number of links increases. For example, assuming a 5 hop system with a required bit error rate of $Pe = 10^{-4}$, a 7dB advantage is achieved by using a digital S&F repeater system instead of an analog repeater system. This improvement may be translated into a 7dB transmitter power reduction (for fixed distances), or extended operating ranges equivalent to 7dB between all repeaters.

TABLE III-II

MESSAGE DELAY AND MESSAGE LOSS RATINGS

Alternative	Message Loss Due to Overlap	Rating	Message Delay	Rating
S&F Digital	Lowest	10	Longest	8
Analog	Highest	8	Shortest	10
Combined	Analog - High Digital - Low	8	Analog - Shortest Digital - Longest (Same as S&F)	10 8

In summary, a multihop system using digital repeaters has a definite (S/N) advantage over a system using analog repeaters. The (S/N) advantage can mean either reduced power requirements or extended ranges. Table III-III indicates, qualitatively, the signal to noise degradation effects of the various repeaters.

TABLE III-III

DIGITAL VS ANALOG REPEATER
SIGNAL TO NOISE RATINGS

ALTERNATIVE	COMMENTS	RATING
Digital	Least Loss	10
Analog	Most Loss	5
Combined	Analog - Most Loss	5
	Digital - Least Loss	10

6.2.2.4 <u>ECM Performance</u>. Since the repeater will monitor the transmissions of many sensors, it has been rather firmly concluded that it would be a prime target of sensor-related ECM activities and attention should therefore be given to optimizing ECM protection. Inasmuch as the out-of-band technique encompasses two 15 MHz frequency bands, as opposed to two 0.5-3 MHz frequency bands for an in-band technique, it is inherently less vulnerable to broadband electronic countermeasures. The in-band repeater offers a potential enemy less bandwidth over which to search for sensor activity and also allows a broadband jammer to concentrate his energy in a narrower band thereby increasing his effectiveness. In fact, this anti-jam property of an out-of-band technique may exceed that of an in-band technique by 17-25dB depending on the specific in-band filter characteristics (considering the A/J protection as a function of bandwidth). Of the in-band repeaters, the digital only repeater provides the maximum ECM protection because it retransmits a very short duration message and also because the repeater channels would not necessarily be contained in two portions of an in-band system and therefore would be more difficult for the enemy to locate. If the digital repeater operates out-of-band it would enjoy additionally the same bandwidth ratio A/J protection as described above for the analog out-of-band and provide maximum protection. Since they do not differentiate between received signals, all analog repeaters function as repeat jammers and this is a serious disadvantage.

TABLE III-IV

ECM RATINGS OF THE THREE ALTERNATIVE REPEATERS

Alternative	Remarks	Rating
Digital	1. Shortest Message - most difficult for the enemy to locate, spot jam and spoof. 2. F_1 - F_1 Mode - Message is retransmitted on the same frequency at each relay - but total transmission time is still much less than analog. 3. F_1 - F_2 Mode - Message is retransmitted on different frequencies and therefor less subject to enemy intercept.	10
Analog	4. Longest Message - Easy for enemy to locate and spot jam. 5. Lack of Decoder - Implies that the relay would be more vulnerable because the relay retransmits any incoming carrier on the operating frequency 6. In-Band Mode - Most vulnerable to spot jamming because relay operation is restricted to two rather narrow bands. 7. Out-of-Band Mode - Provides the most A/J protectinn because of the large bandwidth ratio.	2
Combined	8. Digital retransmissions 1, 3, and either 6 or 7 apply. 9. Analcg retransmissions 4 and 6 or 7 also a Decoder eliminates the vulnerability cited in 5.	Digital 10 Analog 7

The combined repeater has the same vulnerability to long duration analog messages as the analog only repeater; however, it has a decoder which eliminates automatic retransmission of unintended signals occuring on its frequency. When retransmitting digital data, the combined repeater has the same ECM advantages as the digital only repeater. Table III-IV indicates some of the ECM considerations for each type repeater and provides a relative ranking at the repeaters.

6.2.2.5 In-Band vs Out-of-Band Antenna Requirements. An out-of-band repeater system will require an antenna system capable of responding to each band of frequencies. Normally, this is accomplished by using two antennas, one for each band. This approach, when considering the configuration and durability requirements of air-drop relays, presents a significant problem in antenna design. Colinear antenna arrays could be built, but not without a special development effort. A more desirable solution would use a single antenna operating as both a center fed half-wave dipole in the high frequency band and a quarter-wave monopole in the low frequency band. Such an antenna would simplify solution to the packaging and shock requirements of an out-of-band repeater, but it also requires that the assigned frequency bands be separated by approximately an octave. An in-band repeater has an advantage over out-of-band techniques in that the common band RF circuitry permits use of a single broadband antenna for both receive and transmit functions. This in turn improves the likelihood of achieving an antenna design which will satisfy the configuration and shock requirements of air dropped repeaters. Table III-V indicates the relative ranking of the in-band and out-of band antenna requirements.

TABLE III-V

IN-BAND VS OUT-OF-BAND ANTENNA RATINGS

ALTERNATIVE	REMARKS	RATING
IN-BAND: Digital; Analog; Combined	Easier to design and fabricate	10
OUT-OF-BAND: Analog; Combined	More difficult to design and fabricate	5

6.2.2.6 Spectrum Utilization - Number of Channels.

6.2.2.6.1 Required. A S&F digital only repeater operating in the $F_1 - F_1$ mode uses the absolute minimum number of frequencies and provides the greatest flexibility in frequency management. When operated in the $F_1 - F_2$ mode, a relay system with five repeaters requires selection of seven frequencies. Note: The maximum number of frequencies required in digital or combined repeater operating in the simple $F_1 - F_2$ mode is n + 2, where n is the number of repeaters. An analog only repeater operating in full duplex $F_1 - F_2$ requires the greatest number of frequencies i.e. 2n + 2 frequencies where n is the number of repeaters.

6.2.2.6.2 Available. An in-band analog or combined repeater necessarily restricts the number of usable channels to the ratio of the isolation filter bandwidth to the sensor system channel bandwidth. Assuming a realizable filter bandwidth of 500 kHz to 3 MHz and a usable channel bandwidth of 50 kHz (including guardband), an in-band repeater would restrict all repeater operations to 10-60 channels, half in each band. An out-of-band analog or combined repeater requires assignment of two bands, it also provides the maximum number of 50 kHz channels (approximately 300) to choose from, and in this sense has an advantage over in-band (which has up to 60 channels) for reducing interference potential. Thus a distinct advantage is held by an out-of-band technique in that the number of channels available for assignment exceeds that of an in-band technique by 5:1 minimum. Table III-VI indicates the number of RF channels (frequencies) required when operating each type of repeater in series multihop.

TABLE III - VI

NUMBER OF CHANNELS (FREQUENCIES)
REQUIRED AND AVAILABLE TO OPERATE THE THREE ALTERNATIVE REPEATERS IN MULTIHOP

Alternative	Numbers of Channels Required	Rating	Number of Channels Available	Rating
Digital	$F_1 - F_1$ -- One frequency (Minimum) $F_1 - F_2$ -- n + 2 frequencies	10 5	Since operation is S&F up to 300 channels in one band only	5
Analog	2 n + 2 frequencies (Maximum)	2	In-Band: 10 to 60 channels Out-of-Band: Since operation is in two bands -300 channels	2 10
Combined	n + 2 frequencies	5	Same as analog	2 10

6.2.2.7 Energy Requirements. Due to the very long analog messages (20 seconds) that must be retransmitted by the analog and combined repeaters, energy consumption is greatest in these repeaters. In addition, the analog only repeater has two receivers which are "on" constantly and therefore requires approximately twice the battery capacity as does a combined repeater. The S&F digital repeater consumes the least amount of energy. Table III-VII indicates the relative battery energy requirements for the three types of repeaters.

TABLE III-VII

ENERGY REQUIREMENT RATINGS OF THE ALTERNATIVE REPEATERS

ALTERNATIVE	REMARKS	RATINGS
Digital	Least Energy	10
Analog	Most Energy	2
Combined	Moderate Energy	6

6.2.3 Versatility. A versatile repeater is one which is capable of retransmitting both analog and digital data. The digital only repeater is not capable of relaying analog messages. The analog only is capable of relaying analog and digital but not decoding any digital header. Therefore, it is primarily for analog retransmission. The combined repeater is truly a versatile repeater in that it is capable of recognizing and relaying both analog and digital messages. Note: A fourth alternative may be considered by inserting a digital "Add-On" module (containing a decoder, etc.) to an analog only repeater. Use of the "Add-On" module on an analog repeater could provide the same versatility as a combined repeater. Table III-VIII indicates the message type versatility of the three repeater alternatives and the "Add-On" alternative.

TABLE III-VIII

MESSAGE TYPE VERSATILITY OF THE
ALTERNATIVE REPEATERS

ALTERNATIVE	REMARKS	RATING
S&F Digital	Not Versatile	1
Analog Only	Moderate Versatility	7
Analog with "Add-on Module"	Versatile	9
Combined	Most Versatile	10

6.2.4 Development Schedule/Risk. The development time schedule and development risk are related items and are therefore considered together. Development of an air delivered repeater involves the most risk in that production of high shock resistant crystals, and rugged antennas for the deployment environment represent areas requiring considerable investigation. Also an area of risk and possible scheduling delay effecting all repeater types is the requirement for low power digital frequency synthesizers. Considerable development may be required to produce a synthesizer requiring less than 100 milliwatts of power. In addition, the in-band technique requires extreme RF isolation which results in some risk in filter design and producibility. Out-of-band techniques, hand emplaced configurations and S&F techniques all pose little or no risk or scheduling problems. Table III-IX indicates the relative risk and scheduling delays which might be experienced with the three repeater alternatives.

TABLE III-IX

SCHEDULING DELAYS AND RISK RATINGS FOR THE THREE REPEATER ALTERNATIVES

ALTERNATIVE	REMARKS	RATINGS
S&F Digital	Least risk and schedule delays for Hand and Air Deployed	10
Analog In-Band	-Most Risk and schedule delay for Air Delivered -Moderate for Hand Emplaced	2 6
Out-of-Band	-Moderate Risk and schedule delay for Air or Hand Emplaced	6
Combined In-Band	-Considerable Risk & schedule delay for Air Delivered -Moderate Risk for Hand Emplaced	4 6
Out-of-Band	-Moderate Risk & schedule delay for Air delivered -Low Risk for Hand Emplaced	6 8

TABLE III - X

RELATIVE LOGISTIC RATINGS FOR ALTERNATIVE REPEATERS

ALTERNATIVE	TEST EQUIPMENT REQUIRED	REPAIR PARTS REQUIRED	MAINT. SKILLS REQUIRED	EQUIPMENT ADJUSTMENTS REQUIRED
DIGITAL	10	10	10	9
ANALOG	9.5	8.5	9.5	10
COMBINED	9	9	9	9

6.2.5 Logistics.

6.2.5.1 Test Equipment Required. It appears that the test equipment requirements for the three types of repeaters would not differ significantly. The minor impact is due primarily to the fact that most test equipment will be of the "Go-No-Go" type.

6.2.5.2 Repair Parts Required. The analog repeater contains the most components and therefore would probably require the most spare parts. The digital only and combined repeaters would require slightly less spare parts.

6.2.5.3 Maintenance Skills Required. At each category of maintenance, it appears only minor differences in maintenance skill levels will be required for the three alternative repeaters.

6.2.5.4 Equipment Adjustments Required. A frequency or RF channel adjustment must be included on all repeaters. In addition the digital and combined repeaters will have switches for setting repeater ID codes. Therefore, the digital and combined repeater may be slightly more complicated, requiring a few more adjustments. Table III-X indicates the relative logistic ratings for the alternative repeaters.

6.2.6 Physical Characteristics. Weight and shape characteristics for hand and air delivered repeaters appear to be of equal ranking for the three alternatives. However, the electronic and battery volume required for the three alternatives (including the in-band or out-of-band alternative) does place a restriction on the minimum sized air delivered repeater that can be built. Table III-XI indicates a general ranking of the volume requirements in a qualitative way. Engineering Analysis 3 will give a more definitive consideration to this criterion.

TABLE III-XI

VOLUME REQUIREMENT RATINGS OF THE THREE ALTERNATIVES

ALTERNATIVES	REMARKS	RATINGS
Digital	Least Volume	10
Analog	Out-of-Band Mode, Moderate Volume	6
	In-Band Mode, Largest Volume	3
Combined	Out-of-Band Mode, Moderate Volume	6
	In-Band Mode, Largest Volume	3

6.2.7 Costs.

6.2.7.1 Research & Development Costs. Research and development costs will be greatest for the in-band air dropped analog and combined repeaters. This is due to the required high shock, high stability, crystal, antennas, and isolation filter developments. In addition, hybrid and LSI technology must be developed for the miniaturization of the electronics for the air delivered repeaters. Lowest R&D costs are assigned to hand emplaced repeaters because of minimum size and weight restrictions. Table III-XII indicates relative R&D cost for the repeater alternatives.

6.2.7.2 Acquisition Costs. Acquisition cost is the cost required to procure and issue the initial number of required relays to the user. The acquisition cost includes the non-recurring engineering and administrative costs and recurring end item and contract management costs. A few repeater components can be identified as high cost items such as the isolation filters for in-band repeaters and the high shock, high stability crystals for air delivered repeaters. Other costs can be attributed to the number of modules or components in the alternative repeater (e.g. analog only repeater will have two receivers and the combined repeater has a decoder). The choice of transmission technique may have an impact on the repeater cost; however, for this analysis only the relative repeater alternative costs are considered, and not transmission techniques. Table III-XIII indicates the relative acquisition cost of the alternative repeaters.

6.2.7.3 Life Cycle Support Costs. Life cycle support costs consist of the costs for crew and maintenance personnel, replacement, ILS (management), transportation, and depot maintenance. It has been decided that the majority of air delivered repeaters used in combat would not be recovered and reused. Therefore, air delivered repeaters will have higher, relative to hand emplaced repeaters, transportation and replacement costs. Also, little or no depot maintenance would be performed on air delivered repeaters and therefore they would have lower depot maintenance costs. Table III-XIV indicates the relative costs of the factors comprising life cycle support costs. The evaluation data are summarized in Table III-XV.

TABLE III-XII

RELATIVE R&D COST RATINGS FOR ALTERNATIVE REPEATERS

ALTERNATIVE		RELATIVE R&D COST	RATING
Digital		Air - Medium	6
		Hand - Lowest	10
Analog:	In-Band	Air - Highest	2
		Hand - Medium	6
	Out-of-Band	Air - High	4
		Hand - Low	8
Combined:	In-Band	Air - Highest	2
		Hand - Medium	6
	Out-of-Band	Air - High	4
		Hand - Low	8

TABLE III-XIII

RELATIVE ACQUISITION COST RATINGS FOR ALTERNATIVE REPEATERS

ALTERNATIVE		RELATIVE ACQUISITION COSTS	RATING
Digital		Air - Medium	6
		Hand - Lowest	10
Analog:	In-Band	Air - High	4
		Hand - Medium	6
	Out-of-Band	Air - High	4
		Hand - Medium	8
Combined:	In-Band	Air - Highest	2
		Hand - Medium	6
	Out-of-Band	Air - High	4
		Hand - Low	8

TABLE III - XIV

RELATIVE LIFE CYCLE SUPPORT COSTS

TYPE REPEATER		PERSONNEL	REPLACEMENT	ILS MGMT	TRANSPORTATION	DEPOT MAINT
Digital	AIR	9	7	10	7	10
	HAND	9	10	10	10	9
Analog In-Band	AIR	8	4	10	6	10
	HAND	6	6	10	8	7
Out-of-Band	AIR	7	6	10	7	10
	HAND	7	8	10	9	8
Combined In-Band	AIR	8	5	10	6	10
	HAND	6	7	10	8	7
Out-of-Band	AIR	7	7	10	7	10
	HAND	7	9	10	9	8

TABLE III - XV

SUMMARY MATRIX OF EVALUATION DATA

	C. Combined	B. Analog Only	A. Digital Only
PERFORMANCE			
RF Isolation	8.0	5.0	10.0
Message Delay	9.0	10.0	8.0
Message Loss	9.0	8.0	10.0
S/N Degradation	7.5	5.0	10.0
ECM	8.5	2.0	10.0
Antenna Requirements	7.5	7.5	10.0
Spectrum Utilization	5.7	4.7	6.7
Energy Requirements	6.0	2.0	10.0
VERSATILITY	9.5	7.0	1.0
SCHEDULE			
Development Time/Risk	6.0	5.0	10.0
LOGISTICS			
Test Equipment	9.0	9.5	10.0
Repair Parts	9.0	8.5	10.0
Maintenance Skills	9.0	9.5	10.0
Equipment Adjustments	9.0	10.0	9.0
PHYSICAL CHARACTERISTICS			
Volume	4.5	4.5	10.0
COSTS			
R&D	5.0	5.0	8.0
Acquisition	5.0	5.5	8.0
Life Cycle Support	8.0	7.9	9.1

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The previous sections of this engineering analysis have described the problem area in which a decision must be made. The viable alternatives to solve the problem have been identified, and in Section 6.0, each of these alternatives were scored against a set of evaluation criteria by the evaluation committee.

The purpose of this section is to utilize the evaluation scores, presented in Section 6.0, together with a set of weighting factors to obtain a ranking of the alternatives. The weighting factors are used to adjust the impact of the evaluation scores on the evaluation criteria. The weighting factors were obtained from the REMBASS Project Manager and members of his staff, and from AMC and TRADOC personnel.

The results of this section can reflect only what is indicated by the data supplied as inputs to the ranking process. Therefore, the result to be expected from this section will be one of the following:

1) One of the alternatives is indicated as the preferred alternative by a large margin;

2) Two or more alternatives are relatively close, but one is indicated clearly as preferred by a small margin; and

3) The ranking of the alternatives is so close that no alternative can be selected as the preferred alternative.

To develop confidence that the alternative selected as the preferred alternative is indeed the preferred alternative with a very small margin of error, two techniques for perturbing the results are used to determine the stability of the ranking of alternatives obtained. These techniques are:

1) After the basic ranking of alternatives has been achieved by the additive weighting technique three other techniques for ranking the alternatives are used. These additional techniques have the properties of emphasizing or de-emphasizing high or low scores. If the same alternative is indicated as the preferred alternative by all of these techniques there can be little doubt that this is the preferred alternative. When the preferred alternative changes as high or low scores are emphasized, information on the stability of the ranking is provided.

2) In Section 8.0 the sensitivity of the ranking of alternatives to the weighting factors for the major evaluation criteria is determined by sequentially varying the major weighting factors between minimum and maximum values. Thus the stability of the ranking to variations in major weighting factors is determined.

Thus the results of Sections 7.0 and 8.0 are the ranking of alternatives and a selection of a preferred alternative if the data permits. Information is provided on how stable this ranking is as some of the input data is perturbed.

7.1 Basic Ranking Technique. The table of evaluation scores presented in Section 6.0 indicates how well each of the alternatives was rated in each of the evaluation criteria. In order that the evaluation scores contribute to the evaluation rating in accordance with the relative importance of the evaluation criteria, weighting factors were used. The evaluation scores of Section 6.0 and weighting factors for each evaluation criterion are processed by additive and other weighting techniques to provide evaluation ratings. REMBASS, AMC, and TRADOC personnel were requested to assign weight values to each of the major evaluation criteria by distributing 100 points among the major evaluation criteria. The more important evaluation criteria should receive a larger number of weighting points. In addition to assigning a nominal weight to each major evaluation criteria, the participants also provided the range of variation from nominal which they expected for each weighting factor. The same procedure was used to assign weighting factors to sub-criteria. The nominal, maximum, and minimum values of the weighting factors used are given in Table IV-XVI.

TABLE III - XVI

WEIGHTING FACTORS

		Nominal Weight: Major Factor	Nominal Weight: Sub Factor	Weight Range: Minimum	Weight Range: Maximum
I	DEPLOYMENT METHODS	.1875		.1250	.2625
	1 Hand Emplacement		.3250		
	2 Air Drop Emplacement		.4650		
	3 Airborne Platform		.2100		
II	PERFORMANCE	.2450		.1750	.3750
	1 RF Isolation		.0925		
	2 Message Delay		.0750		
	3 Message Loss		.1400		
	4 S/N Degradation		.1225		
	5 ECM Vulnerability		.1825		
	6 Antenna Requirements		.1150		
	7 Spectrum Utilization		.1250		
	8 Energy Requirements		.1475		
III	VERSATILITY	.1850		.1525	.2700
IV	DEVELOPMENT/SCHEDULE RISK	.0800		.0475	.1575
V	LOGISTICS	.0800		.0600	.1325
	1 Test Equipment		.2750		
	2 Repair Parts		.2000		
	3 Maintenance Skills		.2625		
	4 Equipment Adjustments		.2625		
VI	PHYSICAL (Volume)	.0850		.0625	.1550
VII	COST	.1375		.0875	.2250
	1 R&D		.2625		
	2 Acquisition		.4750		
	3 Life Cycle Support		.2625		

The weights provided by the participants were given to two significant figures. To obtain values for Table III-XVI these weights were divided by 100 to make the sum of the weights of major criteria (and subcriteria within each major criterion) equal to 1. Then the weights were averaged and entered in Table III-XVI with four significant figures, three of which are accurate. An evaluation rating is computed for each alternative by multiplying the relative score for a given criterion by the weighting factor assigned to that criterion. The result is a number which represents a combination of the relative importance of the criterion and the evaluation score of the alternative for that criterion. The additive weighting technique used to obtain an evaluation rating is:

$$ER = \sum_{j=1}^{n} W_j \left(\sum_{k=1}^{r_j} S_{jk} \alpha_{ijk} \right)$$

Where:

ER	=	Evaluation Rating
α_{ijk}	=	Relative Evaluation Score for Alternative i for Subcriterion k of Major Criterion j
S_{jk}	=	Weighting Factor for Subcriterion k of Major Criterion j
W_j	=	Weighting Factor for Major Criterion
n	=	Number of Major Criteria
rj	=	Number of Subcriteria of Major Criterion j

Table III-XVII lists the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion. The evaluation scores in this table are accurate to two significant figures. The last line is the evaluation rating or weighted score for each alternative. To illustrate how each value listed in the evaluation rating line was obtained, a sample calculation for one of the alternatives using additive weighting is presented.

TABLE III - XVII

EVALUATION SCORES

				A	B	C
I	DEPLOYMENT METHODS	.1875				
	1 Hand Emplacement		.3250	10.0	10.0	10.0
	2 Air Drop Emplacement		.4650	10.0	10.0	10.0
	3. Airborne Platform		.2100	10.0	10.0	10.0
II	PERFORMANCE	.2450				
	1 RF Isolation		.0925	10.0	5.0	8.0
	2 Message Delay		.0750	8.0	10.0	9.0
	3 Message Loss		.1400	10.0	8.0	9.0
	4 S/N Degradation		.1225	10.0	5.0	7.5
	5 ECM Vulnerability		.1825	10.0	2.0	8.5
	6 Antenna Requirements		.1150	10.0	7.5	7.5
	7 Spectrum Utilization		.1250	6.7	4.7	5.7
	8 Energy Requirements		.1475	10.0	2.0	6.0
III	VERSATILITY	.1850		1.0	7.0	9.5
IV	DEVELOPMENT/SCHEDULE RISK	.0800		10.0	5.0	6.0
V	LOGISTICS	.0800				
	1 Test Equipment		.2750	10.0	9.5	9.0
	2 Repair Parts		.2000	10.0	8.5	9.0
	3 Maintenance Skills		.2625	10.0	9.5	9.0
	4 Equipment Adjustments		.2625	9.0	10.0	9.0
VI	PHYSICAL (Volume)	.0850		10.0	4.5	4.5
VII	COST	.1375				
	1 R&D		.2625	8.0	5.0	5.0
	2 Acquisition		.4750	8.0	5.5	5.0
	3 Life Cycle Support		.2625	9.1	7.9	8.0
	EVALUATION RATING			7.94	6.79	7.87

ALTERNATIVE KEY

A - Digital
B - Analog
C - Combined

Consider Alternative A of Table III-XVII. The weighting factor for Hand Emplacement (.325) and the relative score for Hand Emplacement (10) were multiplied. Similar products were formed for Air Drop Emplacement and Airborne Platform. The resultant products were added, and the sum multiplied by the Deployment Methods Weighting Factor (.1875), Producing the overall Deployment Methods Weighted Score. Similar calculations were performed for each of the other major criteria, producing overall weighted scores for Performance, Versatility, Development/Schedule Risk, Logistics, Physical Characteristics and Cost. Each of these major criterion overall weighted scores were added together, the sum appearing in the last line under EVALUATION RATING. This is the total weighted score for the Alternative A using the additive weighting technique.

The calculations described above are given below for illustrative purposes:

```
7.94 = [.1875][(.3250)(10.0)+(.4650)(10.0)+(.2100)(10.0)]
     +[.2450][(.0925)(10.0)+(.0750)( 8.0)+(.1400)(10.0)+(.1225)(10.0)
          +(.1825)(10.0)+(.1150)(10.0)+(.1250)( 6.7)+(.1475)(10.0)]
     +[.1850][ 1.0]
     +[.0800][10.0]
     +[.0800][(.2750)(10.0)+(.2000)(10.0)+(.2625)(10.0)+(.2625)( 9.0)]
     +[.0850][10.0]
     +[.1375][(.2625)( 8.0)+(.4750)( 8.0)+(.2625)( 9.1)]
```

The data presented in Table III-XVII is a combination of information extracted directly from Section 6.0 plus information that is consolidated from Section 6.0.

Data consolidation was necessary in the following areas:

Message Loss	Versatility
Message Delay	Development/Schedule Risk
S/N	Physical Characteristics
ECM	R&D Cost
Antenna Requirements	Acquisition Cost
Spectrum Utilization	Support Cost

In all cases the data was consolidated by averaging. This technique was recommended by the Subsystem Team to resolve the problems created by evaluating the alternatives on the basis of in-band and out-of-band techniques or where two separate entries are supplied for the combined alternative. This initial analysis indicates that the digital and combined alternatives are preferred. The rankings are too close to confidently select one above the other. Both are definitely preferred above the analog alternative.

7.2 Secondary Ranking Techniques. The additive weighting analysis technique is a valid procedure for evaluating alternatives. The basic advantage is that it considers all pertinent criteria in comparing alternatives, rather than a limited selection of criteria. The technique does suffer since the values for weights and relative scores are assigned based on the judgement of the participating contributors. The results are subject to variation to a degree dependent upon the judgement of the evaluators.

In order to determine if variations in judgement in assigning values to scores will have a significant effect upon the final evaluation, three additional mathematical techniques are utilized in computing evaluation ratings. These additional techniques have the intrinsic effect of biasing the results up or down and simulate the effect of using input scores of greater or lesser value. The secondary techniques are listed below with a brief description of each method and its effect upon the basic data.

7.2.1 RMS Weighting. The resultant evaluation rating is the square root of the sum of the products of the evaluation score squared times its appropriate weighting factor. This can be expressed as follows:

$$ER = \sqrt{\sum_{j=1}^{n} \omega_j \left(\sum_{K=1}^{r_j} S_{jK} a^2_{ijK} \right)}$$

This method places greater emphasis on high scores.

7.2.2 Multiplicative Weighting. The resultant evaluation rating is the product of all evaluation scores raised to the power of their appropriate weight. This can be expressed as follows:

$$\mathrm{ER} = \prod_{j=1}^{n} \left(\prod_{K=1}^{r_j} \alpha_{ijK}^{S_{jK}} \right)^{\omega_j}$$

This method places greater emphasis on low scores.

7.2.3 Logarithmic Weighting. The resultant evaluation rating is the logarithm of the sum of the products of 2 raised to the evaluation score power times its appropriate weight. This can be expressed as follows:

$$\mathrm{ER} = \log_2 \left[\sum_{j=1}^{n} \omega_j \left(\sum_{K=1}^{r_j} 2^{\alpha_{ijK}} S_{jK} \right) \right]$$

This method places extreme emphasis on high scores.

The same basic data used in computing evaluation rating by the additive technique are used in computing evaluation rating by the three secondary techniques described above. The method of computation was generally the same as described except that the appropriate equation and mathematical manipulations were substituted in each case. The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Table III-XVIII.

7.3 Comparison of Results Using Nominal Values. Referring to Table III-XVIII, it appears that the digital alternative is most preferred. Combined is ranked second with the analog alternative consistently last.

TABLE III - XVIII

ALTERNATIVE EVALUATION RATINGS FOR THE FOUR ANALYTICAL TECHNIQUES USING NOMINAL VALUES

ALTER-	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
NATIVE	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
A	7.94	1	8.64	1	6.25	2	9.42	1
B	6.77	3	7.19	3	6.23	3	8.35	3
C	7.87	2	8.12	2	7.59	1	8.81	2

ALTERNATIVE KEY

A - Digital
B - Analog
C - Combined

8.0 SENSITIVITY ANALYSIS

The evaluation ratings used to determine the ranking of the alternatives are computed from the evaluation scores and the weighting factors assigned to each of the major and minor evaluation criteria. The weighting factors are determined by knowledgeable individuals to adjust for the relative importance of each of the evaluation criterion. Because the weighting factors are based on the judgement of individuals, the sensitivity study is used to determine the effect on the ranking of alternatives caused by expected variations in judgement.

The expected variation in each weighting factor is obtained by asking the individuals who supply the nominal weighting factors to supply also their estimates of maximum and minimum values. The weighting factors used for this engineering analysis are given in Table III-XVI.

To determine the sensitivity of the variations in weighting factors for the major evaluation criteria, the weighting factors are varied between maximum and minimum values. This process provides information on the stability of ranking of the alternatives determined in Section 7.0 as the major weighting factors are varied. Because the impact of the weights for the minor evaluation criteria on the evaluation ratings is much less than that for the weights of the major evaluation criteria, a sensitivity study considering the weights of minor evaluation criteria was not considered necessary. By combining the sensitivity study and the use of the different weighting techniques described in Section 7.0, information is obtained on the stability of the ranking of alternatives to variation in weighting factors, as well as to variations in evaluation scores. Rather than vary the scores of all the criteria individually, this technique approximates this function by alternately emphasizing high scores and then low scores.

8.1 Sensitivity Study Using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 14 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 7 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately. The results of the additive weighting sensitivity study are plotted in Figure 3-11. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. An examination of Figure 3-11 reveals that the digital and combined alternatives are closely grouped. Both are rated significantly above the analog alternative. The digital and combined alternatives exhibit the largest separation when the versatility criterion weight is maximized. This seems to be logical as the combined alternative is the most versatile of those considered.

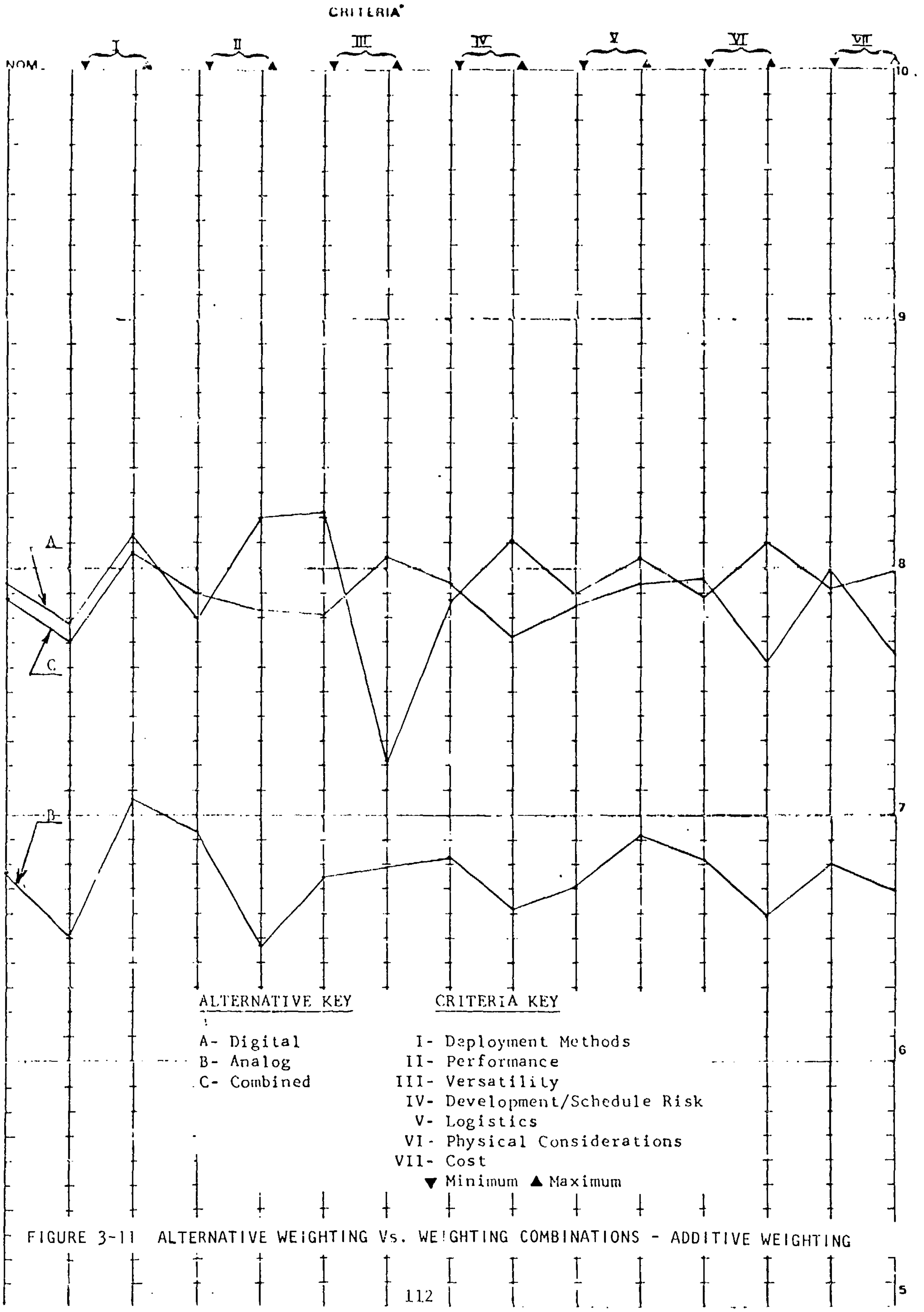


FIGURE 3-11 ALTERNATIVE WEIGHTING Vs. WEIGHTING COMBINATIONS - ADDITIVE WEIGHTING

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 60 sensitivity runs, including the additive nominal reference were made for the analysis. Tables III-XIX through III-XXV shows the computational results from the processing. These results contain the final ER and Rank order as the criterion weighting factors were varied, in four techniques.

TABLE III-XIX

ALTERNATIVE EVALUATION RATING FOR THE FOUR ANALYTICAL TECHNIQUES USING DEPLOYMENT METHODS MINIMUM & MAXIMUM WEIGHTING FACTORS.

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	7.78	1	8.53	1	6.02	2	9.37	1
B	6.52	3	6.93	3	6.01	3	8.09	3
C	7.71	2	7.96	2	7.43	1	8.67	2
MAX								
A	8.13	1	8.77	1	6.52	2	9.49	1
B	7.07	3	7.49	3	6.51	3	8.61	3
C	8.07	2	8.31	2	7.79	1	8.97	2

WEIGHTS USED IN THESE RUNS

MIN Dpt Mtd = .1250, PERF = .2638, VERS = .1992, RISK = .0862,
LOG = .0862, PHYS = .0915, COST = .1481,

MAX = .2625, PERF = .2224, VERS = .1679, RISK = .0726,
LOG = .0726, PHYS = .0772, COST = .1248,

ALTERNATIVE KEY

A- Digital
B- Analog
C- Combined

TABLE III-XX

ALTERNATIVE EVALUATION RATINGS FOR THE FOUR ANALYTICAL TECHNIQUES USING PERFORMANCE MINIMUM & MAXIMUM WEIGHTING FACTORS.

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PERF								
A	7.80	2	8.56	1	6.02	3	9.39	1
B	6.93	3	7.31	3	6.45	2	8.42	3
C	7.90	1	8.16	2	7.60	1	8.87	2
MAX PERF								
A	8.20	1	8.80	1	6.69	2	9.48	1
B	6.47	3	6.95	3	5.85	3	8.21	3
C	7.83	2	8.05	2	7.58	1	8.70	2

WEIGHTS USED IN THESE RUNS

MIN PERF; Opt Mtd = .2049; PERF = .1750; VERS = .2022; RISK = .0874;
LOG = .0874; PHYS = .0929; COST = .1502;

MAX PERF; = .1552; PERF = .3750; VERS = .1531; RISK = .0662;
LOG = .0662; PHYS = .0704; COST = .1138;

ALTERNATIVE KEY

A- Digital
B- Analog
C- Combined

TABLE III-XXI

ALTERNATIVE EVALUATION RATINGS FOR THE FOUR ANALYTICAL TECHNIQUES USING VERSATILITY MINIMUM & MAXIMUM WEIGHTING FACTORS.

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN VERS								
A	8.22	1	8.81	1	6.72	2	9.48	1
B	6.76	3	7.20	3	6.20	3	8.39	3
C	7.81	2	8.06	2	7.53	1	8.78	2
MAX VERS								
A	7.22	2	8.18	2	5.16	3	9.27	1
B	6.79	3	7.17	3	6.31	2	8.2[illegible]	3
C	8.04	1	8.27	1	7.77	1	8.90	2

WEIGHTS USED IN THESE RUNS

MIN VERS; Dpt Mtd = .1950; PERF = .2548; VERS = .1525; RISK = .0832;
LOG = .0832; PHYS = .0884; CHST = .1430;

MAX VERS; = .1679; PERF = .2194; VERS = .2700; RISK = .0717;
LOG = .0717; PHYS = .0761; CHST = .1232;

ALTERNATIVE KEY

A- Digital
B- Analog
C- Combined

TABLE III-XXII

ALTERNATIVE EVALUATION RATINGS FOR THE FOUR ANALYTICAL TECHNIQUES USING DEVELOPMENT SCHEDULE/RISK MINIMUM & MAXIMUM WEIGHTING FACTORS.

ALTER- NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN RISK								
A	7.87	2	8.59	1	6.14	3	9.40	1
B	6.83	3	7.26	3	6.28	2	8.40	3
C	7.94	1	8.18	2	7.66	1	8.86	2
MAX RISK								
A	8.11	1	8.76	1	6.50	2	9.48	1
B	6.62	3	7.03	3	6.12	3	8.24	3
C	7.72	2	7.96	2	7.44	1	8.71	2

WEIGHTS USED IN THESE RUNS

MIN RISK: Dpt Mtd = .1941, PERF = .2537, VERS = .1915, RISK = .0475
LNG = .0828, PHYS = .0880, CNST = .1424,

MAX RISK: ? = .1717, PERF = .2244, VERS = .1694, RISK = .1575
LNG = .0733, PHYS = .0778, CNST = .1259,

ALTERNATIVE KEY

A- Digital
B- Analog
C- Combined

TABLE III-XXIII

ALTERNATIVE EVALUATION RATINGS FOR THE FOUR ANALYTICAL TECHNIQUES USING LOGISTICS MINIMUM & MAXIMUM WEIGHTING FACTORS.

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN LOG								
A	7.90	1	8.41	1	6.19	2	9.41	1
B	6.71	3	7.13	3	6.18	3	8.51	3
C	7.85	2	8.10	2	7.57	1	8.81	2
MAX LOG								
A	8.04	1	8.71	1	6.41	2	9.45	1
B	6.92	3	7.34	3	6.38	3	8.45	3
C	7.94	2	8.17	2	7.67	1	8.83	2

WEIGHTS USED IN THESE RUNS

MIN LOG, Opt Mtd = .1916, PERF = .2503, VERS = .1890, RISK = .0817
LOG = .0600, PHYS = .0868, COST = .1405,

MAX LOG, = .1768, PERF = .2310, VERS = .1744, RISK = .0754
LOG = .1325, PHYS = .0801, COST = .1297,

ALTERNATIVE KEY

A- Digital
B- Analog
C- Combined

TABLE III- XXIV

ALTERNATIVE EVALUATION RATINGS FOR THE FOUR ANALYTICAL TECHNIQUES USING PHYSICAL CHARACTERISTICS MINIMUM & MAXIMUM WEIGHTING FACTORS.

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PHYS								
A	7.89	2	8.60	1	6.17	3	9.41	1
B	6.82	3	7.24	3	6.28	2	8.38	3
C	7.96	1	8.19	2	7.69	1	8.85	2
MAX PHYS								
A	8.10	1	8.75	1	6.47	2	9.48	1
B	6.59	3	7.02	3	6.08	3	8.24	3
C	7.62	2	7.90	2	7.30	1	8.70	2

WEIGHTS USED IN THESE RUNS

MIN PHYS: Dpt Mtc = .1921; PERF = .2510; VERS = .1895; RISK = .0820
LMG = .0820; PHYS = .0625; CMST = .1409;

MAX PHYS: = .1732; PERF = .2263; VERS = .1708; RISK = .0739
LMG = .0739; PHYS = .1550; CMST = .1270;

ALTERNATIVE KEY

A- Digital
B- Analog
C- Combined

TABLE III-XXV

ALTERNATIVE EVALUATION RATINGS FOR THE FOUR ANALYTICAL TECHNIQUES USING COST MINIMUM & MAXIMUM WEIGHTING FACTORS.

ALTERNATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN COST								
A	7.92	2	8.66	1	6.14	3	9.47	1
B	6.81	3	7.25	3	6.25	2	8.41	3
C	8.00	1	8.23	2	7.72	1	8.88	2
MAX COST								
A	7.98	1	8.61	1	6.43	2	9.35	1
B	6.69	3	7.09	3	6.20	3	8.24	3
C	7.66	2	7.93	2	7.37	1	8.69	2

WEIGHTS USED IN THESE RUNS

MIN COST; Dpt Mtd = .1984; PERF = .2592; VERS = .1957; RISK = .0846
LOG = .0846; PHYS = .0899; COST = .0875;

MAX COST; = .1685; PERF = .2201; VERS = .1662; RISK = .0719
LOG = .0719; PHYS = .0764; COST = .2250;

ALTERNATIVE KEY

A- Digital
B- Analog
C- Combined

The relationship among the evaluation scores for each alternative, the nominal weighting factors for the subcriteria and for the major criteria is as shown in Table III-XVII. Table III-XVI additionally includes the maximum and minimum values for the major criteria. The rankings appearing on Tables III-XIX through III-XXV were summarized and are displayed below:

CUMULATIVE RANK FREQUENCY ALL METHODS

ALT	MODE	MEAN	1ST	2ND	3RD
A	1	1.433	39	16	5
B	3	2.917	0	5	55
C	2	1.650	21	39	0

ALTERNATIVE KEY

A- Digital
B- Analog
C- Combined

This Table shows that digital is slightly preferred over the combined alternative. Analog is definitely the least preferred. These results support the conclusion drawn in 7.0. Digital and combined cannot be distinguished, but are both preferred over analog. Greater insight into the results can be determined through a more detailed examination of the scores of Table III-XVII. Deployment methods contribute nothing to the decision process since all alternatives are rated equally. In all categories except versatility, the digital alternative is scored highest or is grouped with the other alternatives at the high end of the scale. Because of this, the digital alternative receives a high weighted score except when the versatility category is weighted heavily (Table III-XXI) or when low scores are emphasized (multiplicative weighting). Attempts to distinguish between the digital and combined alternatives should concentrate on the versatility criteria. With a weight of .185 for this criteria and a relative score of 1 for the digital alternative, digital is slightly preferred over combined. If the weighting is increased either by raising .185 or by emphasizing the low score of 1, combined is preferred. Any decision should be based on a large extent on versatility.

9.0 CONCLUSION

An all digital repeater design was found to be ranked slightly above a combined digital/analog design. If the requirement for analog data transmission is eliminated, the decision as to the repeater type will have been made regardless of the analysis.

10.0 RECOMMENDATION

It is recommended that digital only repeater types be designed, with the decision on digital/analog combined design be based on the requirement to transmit analog data.

SECTION IV

ENGINEERING ANALYSIS 3 - REPEATER CONFIGURATION

1.0 SUMMARY

This analysis addresses the configuration radio of repeaters that will be used in the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated against a specific set of criteria; physical characteristics, versatility, human factors, logistics, schedule, reliability, and cost. The analysis concluded that a single configuration with common electronics was preferred.

The Data Transmission Team reviewed the results and did not agree with the analysis. The team recommended that a separate configuration with common electronics be used for hand and air delivered repeaters.

2.0 INTRODUCTION

The REMBASS system is composed of several major subsystems. Many different alternative subsystem designs may be found which provide the system operational and functional requirements of REMBASS within certain constraints. In order to determine which subsystem alternative provides the best choice, alternatives are evaluated and analyzed against common criteria and one or more possible alternatives are selected as candidates for final system components. This report addresses those criteria which are pertinent to the selection of an optimum packaging configuration for the Hand-Emplaced (HERR) and Air-Delivered (ADRR) Radio Repeaters for the DTS.

3.0 STATEMENT OF THE PROBLEM

Data for REMBASS, both digital and analog, must be transmitted from distant sensors to a readout terminal. In some cases, line-of-sight restrictions or extended ranges will be overcome by deployment of radio repeaters. Radio repeaters will be either HERR or ADRR at the desired location. ADRR repeaters must be capable of withstanding severe shock and environmental conditions and must perform in a hostile environment after deployment.

The problem addressed in this analysis is to determine the optimum packaging configurations for the REMBASS HERR and ADRR repeaters.

4.0 ALTERNATIVES

Four alternative packaging techniques will be analyzed and evaluated to determine which technique most nearly satisfies the REMBASS requirements.

These are:

a) one physical configuration and standard electronics for all repeaters;

b) separate configuration and common electronics;

c) separate configuration and unique electronics; and

d) one configuration and unique electronics.

The HERR and ADRR repeaters may be either a digital only repeater, an analog only repeater, or an analog and digital combined repeater. The analog only repeater and the combined repeater may be either in-band or out-of-band. DTS engineering analysis 2 entitled "Repeater Types" defines and considers the different data to be relayed and the frequency translation technique to be employed. Except as noted in this analysis, the HERR and ADRR radio repeaters are capable of transmitting digital or in-band/out-of-band analog data. It is further assumed that LSI or Hybrid technology will be used for the electronics to the maximum extent practical. Modular units can either contain many functions in one module (i.e., transmitter, decoder, encoder, synthesizer, etc.) or only one function per module. The batteries can be either lithium or alkaline and are designed for 0°F temperatures and 60-day life. (Ref. DDR&E Report, March 1973).

This engineering analysis is concerned solely with HERR and ADRR repeaters and their physical and electronic configuration.

4.1 <u>One Physical Configuration and Standard Electronics for All Repeaters</u> (henceforth known as Alternative A; Same Configuration - Same Electronics). This alternative implies that the same physical package configuration would be used for both HERR and ADRR with identical electrical components found in both. Because of the more stringent size limitations and shock requirements for the ADRR, the configurations and electronics of both repeaters must be designed toward the worst case ADRR. The unit will be cylindrical in shape, as dictated by aerodynamic requirements imposed by air delivery. The switches and controls will either be inset into the cylinder face, or be recessed into one end. One end of the cylinder will contain the batteries and the other will house the electronics. The electronics can be modular units similar to the present Phase III Common Modules or an integrated unit (See engineering analysis DTS 4 entitled, "Equipment Construction Methods"). The antenna will be self-deployed and self-orienting to the vertical. The batteries and electronics will be form-fitted for insertion into a cylindrical delivery vehicle. Directional antennas will not be used because self-aiming is impractical in the ADRR. The unit can be emplaced on the ground or designed to hang up in trees. Hybrid or LSI miniaturization will be required to meet the size and weight requirements of the REMBASS Material Need (MN).

4.2 Separate Configuration and Common Electronics (henceforth known as Alternative B; Different Configuration - Same electronics). This alternative specifies common interchangeable electronics for both the HERR and ADRR but different packaging configurations. The common electronics for both repeaters must be capable of withstanding severe shock as dictated by the ADRR requirements.

4.2.1 ADRR. Same description as applies to Alternative A, 4.1 above.

4.2.2 HERR. The HERR will use the same electronics as the ADRR but may be configured differently for emplacement stability. For example, the packaged configuration could consist of two short cylinders connected by a flat rectangular strip containing the operating centrals and switches (a configuration like the existing SEAOPSS (DIRID). A directional antenna may be used. The cylinders will have end plates secured by screws with one cylinder used for electronics and another for batteries. The package does not have to stand the shock associated with air delivery and the antenna self orientation and erection mechanism may be omitted. Alternately, the HERR could also be made of two boxes joined to form a cubic shape (e.g. EMID configuration). The upper portion would contain the electronic modules while the lower case would contain the battery. A dust cover would be provided for the electronic portion of the box. The switches would be located on top of the box or inside and a directional antenna could be used.

4.3 Separate Configuration and Unique Electronics (henceforth known as Alternative C; Different Configuration - Different Electronics).

The electronics and packaging configuration are both unique and will be optimized depending on the type of deployment. The electronics will not be interchangeable between HERR and ADRR.

4.3.1 ADRR. Same description applies as to Alternative A, 4.1 above.

4.3 2 HERR. The unit would probably be cubic or a rectangular box with the lower case containing the form fitted battery and with the upper case containing the electronics. The electronics do not have to meet severe shock requirements nor do they have to be extensively miniaturized. The electronics may be placed on PC plug-in boards. A dust cover will be provided to protect the boards. All knobs and switches may be on the top of the package. A directional antenna may be provided. Provisions will be made for test points on the upper case (protected from the elements) to provide for rapid trouble shooting of the electronics. Major functions, i.e., transmitter, decoder, encoder, etc., can be placed on separate PC boards. Thus repair of electronic failure would require only replacement of defective boards.

4.4 One Configuration and Unique Electronics (henceforth known as Alternative D; Same Configuration - Different Electronics). In this alternative, the packaging configuration will be the same for both air and hand emplaced repeaters; however, the electronics would be unique. Certain mechanical modules necessary for antenna deployment in ADRR will not be found in HERR and the components need not meet all air delivery shock requirements.

4.4.1 ADRR. Same description as Alternative A, 4.1 above.

4.4.2 HERR. The electronics would be modules which would fit into a cylindrical tube (delivery vehicle). A directional antenna may be affixed to the tube housing using a special adapter. Since a mechanical module would not be needed for antenna deployment, the available space may be used for either batteries or electronics. Special care would have to be taken to prevent mix-up and interchanging of modules between HERR and ADRR since both would fit into the tube but the HERR electronics will not meet air delivery shock requirements. This alternative should be eliminated from further consideration because it provides no advantage technically and is operationally impossible.

5.0 CRITERIA

The criteria which will be used in the comparative evaluation of the alternatives associated with this engineering analysis are defined in this section. In Section 6.0 each alternative is evaluated against these criteria. Then each alternative is ranked against other alternatives for each criterion and a relative ranking is presented for each major criterion. This data will be used in Section 7.0 to make a comparative analysis of the alternatives to determine which most nearly meets the REMBASS requirements.

5.1 Deployment Methods. The REMBASS MN requires that repeaters be emplaced by various means. How these requirements impact the design, construction, etc., of the various alternatives will be considered.

5.1.1 Hand-Emplacement. This is a method of deployment which requires foot troops to carry the repeater to the desired installation location. Size, shape, and especially weight are critical factors for this criterion.

5.1.2 Air-Drop Emplacement. This method implies that the repeater may be emplaced from a fixed wing or rotary wing aircraft. The repeater may be dispensed by hand, from a SUU-42 type dispenser or from special bomb racks such as the PMBR.

5.2. Physical Characteristics.

5.2.1 Size. The physical dimensions of the repeater are critical, not only for hand carrying ability, but also because of the requirement to drop repeaters from available aircraft dispensers such as the SUU-42.

5.2.2 Weight. The constraint on weight is a significant criterion for hand-emplaced sensors and is limited by the MN to 25 lbs.

5.2.3 Shape. Along with size, this parameter is critical for hand-carrying ability, use of available aircraft dispensers for air drop emplacements, and ease of being serviced and repaired by personnel.

5.3 Versatility. This is the extent of commonality of electronics and/or packaging configurations between HERR and ADRR.

5.4 Human Factors. This is the extent of man/equipment interfacing which would include ease of changing batteries, electronic modules, ID codes, manipulating switches, and emplacement of HERR.

5.5 Logistics. The logistics aspect of each alternative is evaluated in terms of the maintenance skills, repair parts, and special test equipment required.

5.5.1 Test Equipment. The special equipment needed to properly support a given repeater in the field.

5.5.2 Repair Parts. The number of unique components necessary to support a repeater in the field in case of failure or malfunction.

5.5.3 Maintenance Skills. The special technical skills required of support personnel in the field.

5.6 Development Schedule/Risk. Schedule and risk are related criteria and determine the extent of development required and the probability of successfully acquiring a particular repeater alternative.

5.7 Spectrum Utilization. This criteria relates to the effectiveness with which a particular alternative uses the assigned frequency band. It is related to the number of relay links which are available, and how frequencies must be assigned to repeaters.

5.8 Energy Requirements. Since the repeaters will generally be required to operate from batteries, the amount of power and energy required is a significant criterion for evaluating alternatives. Standby power and energy per message are measures of comparison.

5.9 Reliability. Mean-time-between-failure for equipment.

5.10 Costs. Costs for each alternative are estimated to include all costs from engineering development, initial purchase, and supply of each army element with the required system components, to the continued resupply of equipments, with supporting costs, for the expected life cycle of the system.

5.10.1 R&D Costs. This is the cost required to develop and test the device to the point where initial production may begin. Extending the state-of-the-art of a required capability may be required in some cases. Included in R&D costs are non-recurring investment costs.

5.10.2 Acquisition Costs. This is the cost required to procure and stock the required Army elements (division, battalion, etc.) with the equipment, spare parts, software, etc., for an initial operational capability. Subsequent costs are covered under life cycle support costs.

5.10.3 Life Cycle Support Costs. These costs are required for replacement items, support personnel, management, transportation, and depot maintenance.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 General.

Field experience with previous sensors indicates that a radio repeater is often required to overcome extended ranges and terrain-imposed, line-of-sight restrictions which accompany sensor system deployment. In this evaluation, attention will be directed to criteria which impact on the physical and electrical configurations for HERR and ADRR. This evaluation will not concern itself with ballistically-emplaced radio repeaters.

6.2 Physical Characteristics. MN for REMBASS specifies that the weight and size of the radio repeater will not exceed 25 lbs and 1 cubic foot respectively, including battery and antenna. This has been interpreted to imply worst case characteristics for hand emplacement and assumes a single channel radio repeater.

6.2.1 Size. Regardless of the packaging configurations, all alternatives meet the maximum volume specified above for HERR. As for the ADRR, there is no MN requirement to specify its weight and volume requirements. Its only restrictions may be the type of dispenser to be used for deployment.

6.2.2 Weight. Table IV-I is a summary of required electronic and battery weight (using LSI technology) estimates taken from a CSTA Lab report entitled, "Sensor Radio Relay,"-presented to ODDR&E, Mar 73. A 60-day battery life at 0°F was assumed. To these figures we must add 11.6 to 15.1 lbs (depending on housing length) for the weights of the housing and self-orientation mechanism (SOM) for antenna deployment for Alternative A & D. The MN weight requirements for HERR may be exceeded by 10 lbs or more for Alternative A (same electronics - same configurations) and Alternative D (same configuration - different electronics) if alkaline batteries are used. The MN weight requirements would be met if lithium batteries are used. Alternative B (same electronics - different configuration) and Alternative C (different electronics - different configuration) are expected to meet the MN weight requirements for HERR regardless of the receiver only if lithium batteries are used. The MN weight requirements will not be met if alkaline batteries are used for the Analog Only In-Band Receiver case. For all other alkaline-receiver combinations, including the Analog Only Out-of-Band Receiver, the MN requirements will probably be met.

6.2.3 Shape. As defined in 4.1, the ADRR will probably be cylindrically shaped since present aerial dispensers are designed for cylindrical units. The HERR could be cubic or dual cylindrically configured (as per 4.2.2 or 4.2.2.1) so that it can be more easily emplaced, serviced, and repaired by personnel. A cylindrical package, mounted on a tripod, need not be ruled out for the HERR. The package shape will ultimately be determined by line of sight deployment requirements (stability, antenna height, etc). Table IV-II indicates ranking of physical characteristics for HERR.

TABLE IV - I

REPEATER WEIGHT REQUIREMENTS

REQUIRED ELECTRONIC (LSI) & BATTERY WEIGHT

TYPE BATTERY USED	WEIGHT LBS*				
	DIGITAL REPEATER	ANALOG ONLY REPEATER		COMBINED REPEATER	
		In-Band	Out-of-Band	In-Band	Out-of-Band
Lithium	7.7	13.5	9.1	9.9	8.1
Alkaline	18.9	34.3	22.3	25.9	20.6

* Exclusive of Housing - add 11.6 to 15.1 lbs to obtain repeater total.

TABLE IV - II
RATINGS OF ALTERNATIVES VS PHYSICAL CHARACTERISTICS

Alternatives		Size	Relative Rating (Note 1)	Shape	Relative Rating	Will configuration allow meeting of MN weight requirements?	Relative Rating
A	HAND	LARGE Will meet MN	8	Cylinder	8	Li - yes	8
						Alk - no	0
	AIR		10	Cylinder	10	Li - yes	8
						Alk - yes	7
B	HAND	LARGE Will meet MN	8	2 Cylinder or Cubic	10	Li - yes	8
						Alk - Analog-InBand-no	0
						Alk - Analog-OutBand-yes	7
						Alk - Other - yes	7
	AIR		10	Cylinder	10	Li - yes	8
						Alk - yes	7
C	HAND	OPTIMUM Will meet MN	10	Rectang-ular box or cylin-der	10	Li - yes	8
						Alk - Analog-InBand-no	0
						Alk - Analog-OutBand-yes	7
						Alk - Other - yes	7
	AIR		10	Cylinder	8	Li - yes	8
						Alk - yes	7
D	HAND	LARGE Will meet MN	8	Cylinder	8	Li - yes	8
						Alk - no	0
	AIR		10	Cylinder	10	Li - yes	8
						Alk - yes	7

Note 1 - Rating for Each Alternative/Criterion are based on criterion data and are given values from 0-10, with highest number indicating highest rating.

6.3 Versatility. The versatility of the various alternatives will depend on:

a) the interchangeability of electronics between packaging configurations; and

b) the interchangeability of physical package configurations (i.e., use the same package for both ADRR and HERR). Table IV-III indicates a relative ranking of the versatility of the configurations.

6.3.1 Alternative A (Same Configuration - Same Electronics). Since the physical configuration and electronics are the same for HERR and ADRR, the equipment is very versatile and can be used for any mission.

6.3.2 Alternative B (Same Electronics - Different Configuration). There will be two different package configurations; one for ADRR and one for HERR; however, both use the same electronics.

6.3.3 Alternative C (Different Electronics - Different Configuration). A different package and electronics will be used depending on the emplacement technique. Thus, the electronics and package are not interchangeable at all.

6.3.4 Alternative D (Different Electronics - Same Configuration). The packaging in this case is the same regardless of emplacement technique. However, the electronics will be different for the ADRR and HERR. This design can be used for all types of radio repeaters and batteries.

TABLE IV-XII

RATINGS OF ALTERNATIVES VS VERSATILITY SUB-CRITERIA

ALTERNATIVE	Number of Physical Packages Needed	(Note 1) Relative Rating	Number of Electronic Designs Needed	(Note 1) Relative Rating	Remarks	Final Rating (Note 2)
A	1	10	1	10	Most Versatile	10.0
B	2	5	1	10	Acceptable	7.5
C	2	5	2	5	Least Versatile	5.0
D	1	10	2	5	Questionable	7.5

NOTES: (1) Ratings for each alternative/criterion are based on criterion data and are given values from 0-10, with highest number indicating highest rating.

(2) Final ratings to be determined by appropriately weighting and combining individual criterion ratings.

6.4 Human Factors. In evaluating the various alternatives for this criterion, the subcriteria previously defined are used. They are the case of: a) changing batteries; b) manipulating switches; c) changing electronic modules; d) changing ID codes; and e) hand carrying and emplacing HERR. Each alternative will be discussed and a rating will be given in the summary. Table IV-IV indicates a relative ranking of configurations in terms of human factors.

6.4.1 Alternative A (Same Configuration - Same Electronics). Since the radio repeater is designed to be air delivered, and assuming the housing to be cylindrically shaped, the ON/OFF switch and recovery code switches will either be covered by the end plate or recessed from the end to prevent damage. Thus the switches are not easily accessible. Likewise, removal of batteries and form fitted electronic modules may be cumbersome and may require special tools in order to open the housing. If the electronic modules themselves are covered by a removable metal or plastic case, the oscillator crystals must be located near the ends of the modules for easy access. Once the electronic modules are removed from the delivery package, there is no problem of access to the crystal. Carrying the 25 lb repeater does not appear to pose a major problem. A shoulder strap can be used to help carry the unit.

6.4.2 Alternative B (Different Configuration - Same Electronics). For the ADRR; 6.4.1 applies. For the HERR as per 4.2.2, the package configuration may consist of two short cylinders (like the DIRID), connected by a flat rectangular strip which will contain all the ON/OFF, arm and recovery code switches. One cylinder would contain the form fitted batteries while the other would house the electronic modules. The batteries and electronic modules would be secured by end plates held in place by 3 screws. The only problem may be dirt in the screw threads. The ON/OFF recovery switches would be externally accessible. The unit would be smaller and lighter than the ADRR as a result of eliminating the automatic antenna deployment mechanism and therefore be easier to carry. The ease of changing frequencies, and crystals will be similar to that found in 6.4.1.

6.4.3 Alternative C (Different Configuration - Different Electronics). For the ADRR; 6.4.1 applies. For HERR configuration, the batteries are easily accessible in the lower case and require no tools for replacement. The electronics would require the removal of set screws in order to remove the PC boards. Once the case is opened, crystals can be replaced. All switches will be external to the unit and easily accessible. The unit would be mechanically stable for ground installation and optimum for manpack. An output plug could be provided as the base of the electronics case to permit rapid checkout of the entire repeater.

6.4.4 Alternative D (Same Configuration - Different Electronics). 6.4.1 is applicable for this case with the added problem of module mix-up between ADRR & HERR since both types would fit into the container.

TABLE IV - IV   Ratings of Alternatives vs Human Factors Criteria

ALTERNATIVES		Changing or Replacing Batteries	Relative Rating (Note 1)	Switch Selection and Adjustments	Relative Ratings	Changing Electronic Modules	Relative Ratings	Changing ID Codes	Relative Ratings	Hand Carrying & Emplacement	Relative Ratings	Final Rating (Note 2)
A	HAND	Cumber-some	7	Cumber-some	7	Cumber-some	7	Cumber-some	7	Moder-ate	8	
	AIR	Cumber-some	7	Cumber-some	7	Cumber-some	7	"	7		-	
B	HAND	Less Cumber-some	9	Easy	10	Less Cumber-some	8	"	7	Easy	10	
	AIR	Cumber-some	7	Cumber-some	7	Cumber-some	7	"	7		-	
C	HAND	Easy	10	Easy	10	Less Cumber-some	8	"	7	Easy	10	
	AIR	Cumber-some	7	Cumber-some	7	Cumber-some	7	"	7		-	
D	HAND	Cumber-some	7	Cumber-some	7	Cumber-some may have Module Mix-Up	5	"	7	Moder-ate	8	
	AIR	Cumber-some	7	Cumber-some	7		5	"	7		-	

NOTES: (1) Ratings for each alternative/criterion are based on criterion data and are given values from 0-10, with highest number indicating highest rating.

(2) Final ratings to be determined by appropriately weighting and combining individual criterion weightings.

6.5 Logistics. For the four configurations presented, the alternative finally chosen will have significant impact upon logistics. The logistical levels considered will be Operator/Organization, Direct Support, General Support, and Depot. Table IV-V is a relative rating for the various parameters concerning logistics.

6.5.1 Test Equipment Required. At the operator/crew level the test equipment required would be the same regardless of the configuration and electronic modules used since only Go/No-Go tests would be conducted. For higher support levels, the choice of configurations has an impact on interface equipment required for testing electronics.

6.5.1.1 Alternative A (Common Electronics - Common Configurations). Test equipment required for this configuration would be minimal. For the various electronic modules, a stack tester would be provided at both the Direct Support and General Support levels to determine inoperable modules. (A stack tester would perform electrical measurements for a given module and would indicate the general fault of that module). The depot would have a more detailed procedure for fault isolation using computer controlled test equipment.

6.5.1.2 Alternative B (Common Electronics - Different Configurations). Test equipment required for this configuration would again be minimal because of the common electronics. Once again a stack tester would be provided for Direct Support and General Support levels. At the Depot level, an additional interface may have to be developed so that computer controlled test equipment could make detailed measurements on the HERR. The same program and test equipment would be used for both HERR & ADRR units.

6.5.1.3 Alternative C (Different Electronics - Different Configurations). Since the electronics are unique and some electrical parameters may be different (e.g. crystal stability), it is envisioned that one computer controlled test set up with two different programs, tolerances, and interface equipment would be required at the Depot level. At the Direct Support and General Support levels, there may be some modifications of interface equipment so that the same stack testers may be used for both the HERR & ADRR.

6.5.1.4 Alternative D (Same Configuration - Different Electronics). Same test equipment as for Alternative C. Table IV-V is a relative ranking of test equipment required to maintain units.

6.5.2 Repair Parts Required. The various alternatives require different amounts of repair parts and replacement parts to be stocked. The final alternative chosen will have significant impact on the various types and number of parts stocked.

6.5.2.1 Alternative A (Same Configuration - Same Electronics). In this case, the least number of parts will be stocked. Since all the packages and electronics are the same, no duplicate inventories would be maintained.

6.5.2.2 Alternative B (Same Electronics - Different Configuration). For this alternative, the number of electronic parts stocked is the same as for Alternative A; however, more mechanical components (switches, cases, etc.) and antennas will have to be stored because of the two different package configurations.

6.5.2.3 Alternative C (Different Configuration - Different Electronics). Since all the parts are different and non-interchangeable, a dual inventory system would be maintained. This alternative would require the greatest number of different parts to be stocked in that electronics, batteries, antennas and various mechanical parts (switches, cases) are completely different for the HERR and the ADRR.

6.5.2.4 Alternative D (Same Configuration - Different Electronics). This alternative requires that dual electronics and antenna be stocked, while mechanical devices would be kept to a minimum. This alternative requires slightly fewer parts than Alternative C, since the mechanical parts and configurations are the same for the HERR and ADRR. Presented in Table IV-V is a relative ranking of repair parts required for the alternatives.

6.5.3 Maintenance Skills Required. The maintenance skills required in the knowledge concerning the electronic and mechanical design required to maintain and repair the equipment is presented only as a relative comparison among the alternatives and is not meant as a definition for the level of skill required to maintain the equipment. The operating and maintenance skills required at the Operator level would be the same regardless of alternatives and thus are not discussed. At the Direct Support, General Support and Depot levels, the relative skills required will depend on the alternatives chosen.

6.5.3.1 Alternative A (Same Electronics - Same Configurations). Relatively speaking, this alternative would require the least amount of skill since there is only one electronic and mechanical system to master.

6.5.3.2 Alternative B (Same Electronics - Different Configurations). For this alternative, only a slightly higher amount of skill is required than Alternative A. Operations of two different types of packages would have to be learned; however, the electronics would still be the same for both configurations.

6.5.3.3 Alternative C (Different Electronics - Different Configurations). For this alternative, two differenct packages and two slightly different electronic systems are used. More training would be required in learning the differences involved with regard to interface equipment, packaging, and electrical parameters than for Alternatives A and B. Thus in relative terms more skill is required in maintaining equipment of this alternative.

6.5.3.4 Alternative D (Same Configuration - Different Electronics). This alternative would require about the same level of skill as Alternative C. A relative rating for the various skill and training needs to repair equipment is presented in Table IV-V.

TABLE IV - V

RATING OF ALTERNATIVES VS LOGISTICS

ALTERNATIVES	TEST EQUIPMENT	RELATIVE RATING	REPAIR PARTS REQUIRED	RELATIVE RATING	MAINTENANCE SKILL	RELATIVE RATING	FINAL RATING
A	Test equipment minimal. Stack tester to check modules. No interface equipment needed.	10	Least since only one set of electronics & packing used.	10	Least only one electronic & mechanical system to master	10	10
B	Test equipment minimal. Interface equipment may be needed.	9	More only one set of electronics needed but two different packages.	8	More only one electronic system to master - Two Mechanical System	9	9
C	Interface equipment needed. May need two different programs in Computer to check out tolerances.	5	Most have two different electronic systems. Also have two different packages.	4	Most two electronic & mechanical systems to master.	5	5
D	Interface equipment needed. May need two different programs in computer to check out tolerances.	5	More has two different electronic systems but only one package.	6	More two electronic systems to master One Mechanical System	5	5

6.6 Schedule/Risk. This section analyzes the schedule, packaging, and electronics risk associated with the deployment method. This analysis is not concerned with the delivery techniques or the delivery package.

The ADRR inherently has a greater risk factor than the HERR because the unit must survive a more severe environment and the relative uncertainty in relay placement. The major areas effecting risk and therefore schedule for the ADRR would be as follows:

a) The implication for some form of large-scale integration (LSI) technology in order to remain within the size constraints associated with this development;

b) Antenna ruggedness and deployment;

c) Development and testing of crystals capable of withstanding shock (while a temperature compensated, voltage controlled, crystal oscillator (TCVCXO) module being developed by the ET&D Lab for the COMM/ADP REMBASS Synthesizer has not yet been shock-tested. There is high confidence that with a properly oriented crystal (the square plane is aligned with the shock axis), the crystal will survive a shock of 15,000 G, 6 msec in duration; and

d) The ADRR in general will tend to represent a more complex mechanical design than the HERR because of the antenna erection mechanisms and the need for a stable aerodynamic trajectory. With these considerations in mind, the worst case applications would be ADRR In-Bank analog only repeater and the combined repeater in-band operation requires the use of larger and more complex filters in order to obtain isolation between transmitter and receiver. However, out-of-band repeaters involve simpler designs since the receive and transmit frequencies are separated by at least an octave. Besides requiring more space in the delivery vehicle, the in-band filters represent a greater development risk because they are more susceptible to failure due to shock.

6.6.1 Alternative A (Same Package - Same Electronics). Since the electronics must meet the worst case configuration (air deployed), risk is considered to be medium to high. Since previous units have been air dropped, the packaging is considered to be of low risk. However, the delivery vehicle and antenna erection mechanism, which are not treated here, are of considerable concern.

6.6.2 Alternative B (Same Electronics - Different Configuration). Since the electronics must meet the worst-case configuration (air deployed), risk is medium to high. For the HERR, packaging configuration is considered to be of little or no risk with a lead time of 6 months. For the ADRR, package configuration is considered to be of low risk.

6.6.3 Alternative C (Different Electronics - Different Package Configuration). For the HERR, packaging is considered to be of no risk; the electronics development risk is also considered to be of no risk.

For the ADRR, packaging is considered to be of low risk. Because of the shock environment and the volume constraints placed upon the ADRR the development of the electronics is considered to be of medium to high risk.

6.6.4 Alternative D (Same Package - Different Electronics). The package to be used for both ADRR and HERR is considered to be a low risk since previous work has been done in Phase III. For the HERR, the electronics development would be considered to be low risk. For the ADRR, the electronics development would be considered of medium to high risk. Table IV-VI is a summary matrix with the levels of risk indicated for each alternative.

TABLE IV-VI

RISK ASSOCIATED WITH ALTERNATIVE CONFIGURATIONS VS DEPLOYMENT METHOD

ALTERNATIVE	RISK LEVEL	HERR	ADRR	RATING
A	Package	Low	Low	10/10
	Electronics	Medium-High	Medium-High	5/5
B	Package	Low	Low	10/10
	Electronics	Medium-High	Medium-Low	5/5
C	Package	Low	Low	10/10
	Electronics	Low	Medium-High	10/5
D	Package	Low	Low	10/10
	Electronics	Low	Medium-High	10/5

6.7 Spectrum Utilization & Number of Channels. Physical configurations will not effect spectrum utilization or the number of channels available.

6.8 Energy Requirements. If lithium batteries and COSMOS logic are used then there appears to be little problem in providing the power required within the space and weight constraints and of providing the required battery life. However, because of its weight and size alkaline batteries may not meet MN requirements (see 6.2.2 Weight) under certain repeater configurations.

6.9 Reliability. Reliability of equipment is directly related to the number of components, quality of components, heat generation, and severity of the environment in which the repeater is used. Using the past performance of Phase III common modules as a guide for HERR electronics, high reliability levels can be expected for all alternatives. For ADRR, additional reliability problems arise; however they will not be considered since they concern deployment rather than electronic operation. These include antenna deployment, repeater location, severe shock environments on crystals, and the fact that larger modules will need greater support from vibrations. Listed in Table IV-VII are reliability ranking for electronics. Since the ADRR will be built toward higher standards, their electronics will consequently have the highest reliability.

TABLE IV-VII

RELATIVE RELIABILITY FOR THE VARIOUS ALTERNATIVES

ALTERNATIVE	RELATIVE RELIABILITY	RATING
A	Air - Highest	10
	Hand - Highest	10
B	Air - High	8
	Hand - High	8
C	Air - Highest	10
	Hand - High	8
D	Air - High	8
	Hand - High	8

6.10 Costs. While the choice of a particular technique will be of considerable importance to the repeater cost, this analysis will consider those costs associated with the packaging and electronic configurations.

6.10.1 Research And Development Costs. R&D costs are dependent on the level of effort required on any individual item and also on the variations or types of items to be developed. Costs are based on the information provided in the REMBASS "Baseline Cost Estimate" (BCE), dated Feb 73. The quantity breakout for 13 ivision force has been modified to eliminate ballistically emplaced repeaters. The quantity reduced has been apportioned to the other type of repeaters shown.

Number of Required Repeaters:

57 per division
X13 divisions
741
+20% for training and pipeline
889 total rounded to 900

Of 900 radio repeaters required, 600 would be HERR and 300 would be ADRR. They are further broken down intthe BCE as follows:

HEDSCRR	325	
HEADSCRR	163	HERR
HEMCRR (Hand - emplaced Multi-channel RR)	112	
AEDSCRR	200	ADRR
AEADSCRR	100	
TOTAL	900	

Figures V-3/20, 3/21, 3/22, 3/23 in the BCE break out for R&D Investment/ Non-Recurring and Recurring Investment (both in-house and contract) for the 13 division force. Since the HEMCRR will be built as a separate item (see engineering analysis 6, entitled, "Number of Channels for Repeater") and since the same number of HEMCRR will be built regardless of the packaging technique used, the cost figures for the HEMCRR have been excluded. Using the REMBASS BCE as a guide, shown in Table IV-VIII is a list of the quantities of each type of repeater required for 13 divisions for the alternative packaging techniques used. As can be seen, the alternatives can be combined into two groups; Alternatives A and B can be combined as can Alternatives C and D. The grouping of Alternatives A and B into a single category can be made since most of the research and development costs will go into the electronics rather than for developing the case.

All cost comparisons in this analysis will be based on the number and type of repeaters required for each alternative as shown in Table IV-VIII. The R&D cost comparison for the various alternatives is shown in Table IV-IX. Note that the R&D costs include non-recurring investment costs. The R&D cost is much larger for alternatives C and D by about 3.4 million, than for Alternatives A and B. The larger cost is primarily due to the cost of developing additional types of repeaters required in Alternative C and D.

TABLE IV - VIII

ELECTRONIC QUANTITY AND TYPE OF REPEATER
REQUIRED FOR EACH ALTERNATIVE

Radio Repeater Type	ALTERNATIVES			
	A	B	C	D
HEDSCRR	*	*	325	325
HEADSCRR	*	*	163	163
AEDSCRR	525	525	200	200
AEADSCRR	263	263	100	100
HEMCRR	112	112	112	112
TOTAL	900	900	900	900

*Electronics are the same as for Air Dropped Repeaters, therefore we will have no HERR from the Electronics point of view for Alternatives A & B.

6.10.2 Life Cycle Support Costs - Life Cycle Support Costs consists of the following: Crew and Maintenance Personnel, Consumption/Replacement, Integrated Logistic Support (ILS), Transportation, and Depot Maintenance. Table IV-IX is a summary of the various costs that comprise Life Cycle Support Costs for a 10 year Life Cycle, 13 division power. The source of these data is the REMBASS Work Break down Structure #1. Baseline Cost Estimates.

Initially, the fact that Alternatives C & D are less expensive than Alternatives A & B appears to be inconsistent with the fact that Alternatives C & D require more types of repeaters and hence should have greater costs. Alternatives A & B have higher life cycle support costs because Alternatives A & B are comprised primarily of air-delivered repeaters which have a higher per-item cost. (Although the number of air and hand delivered units is the same regardless of alternative, the electronics for Alternatives A & B will meet the more rigid and costlier air dropped requirements and therefore can be said to be primarily composed of air delivered repeaters.) The Life Cycle Support Costs for the Alternatives C & D would cost less by approximately 2.3 million as compared to Alternatives A & B.

6.10.3 Acquisition Cost - As indicated in Annex B of BCE, the acquisition costs represent the following: Hardware, Spare and Repair Parts, Training, Production Engineering and PMO. Table IV- X is a summary of acquisition costs for the various alternatives. Alternatives C and D are about $600K less than Alternatives A and B. The lower acquisition cost figure for Alternatives C & D is due primarily to the lower unit cost for hand emplaced repeaters.

Table IV- X is a summary of all the costs along with their relative and final ratings.

TABLE IV - IX LIFE CYCLE COST FOR VARIOUS ALTERNATIVES

ALTERNATIVES	CONSUMPTION/ REPLACEMENT	ILS	TRANS	DEPOT	PERSONNEL	TOTAL	RATING
A & B	12,520.4K	6,147K	35.6K	20.3K	251.2K	18,974.5K	8
C & D	10,592.2K	5,800K	24.2K	11.3K	251.2K	16,678.9K	10

TABLE IV - X COST BREAKOUT FOR VARIOUS ALTERNATIVES

ALTERNATIVE	HERR Quantity	HERR R&D Costs	ADRR Quantity	ADRR R&D Costs	Total	Relative R&D Rating	Life Cycle Costs Total	Relative Life Cycle Rating	Acquisition Cost	Relative Acquisition Cost Rating	Total Costs
A Same Package Same Electronics			788(1)	5,419K	5,419K	10	18,974K	8	2,175K	8	26,568K
B Different Package Same Electronics			788(1)	5,419K	5,419K	10	18,974K	8	2,175K	8	26,568K
C Different Package Different Electronics	488(1)	3,361K	300	5,419K	8,780K	7	16,679K	10	1,622K	10	27,081K
D Same Package Different Electronics	488(1)	3,361K	300	5,419K	8,780K	7	16,679K	10	1,622K	10	27,081K

(1) Does not include costs for 112 HEMCRR (Hand Emplaced Multi Channel Radio Repeaters)

TABLE IV - XI

SUMMARY RATINGS OF ALTERNATIVES VS. CRITERIA

ALTERNATIVES		COSTS: R&D	COSTS: ACQUISITION	COSTS: LIFE CYCLE SUPPORT	VERSATILITY	PHYSICAL CHAR.: SIZE	PHYSICAL CHAR.: WEIGHT	PHYSICAL CHAR.: SHAPE	HUMAN FACTORS	LOGISTICS: TEST EQUIPMENT	LOGISTICS: REPAIR PARTS	LOGISTICS: MAINTENANCE SKILLS	DEVELOPMENT SCHEDULE/RISK	SPECTRUM UTILIZATION	ENERGY REQUIREMENTS	RELIABILITY
A	HAND	10	8	8	10	8	10	8	7.8	10	10	10	7.5	--	10	10
	AIR	10	8	8	10	10	10	10	7.8	10	10	10	7.5	--	10	10
B	HAND	10	8	8	7.5	8	10	10	9.8	9	8	9	7.5	--	10	8
	AIR	10	8	8	7.5	10	10	10	7.3	9	8	9	7.5	--	10	8
C	HAND	7	10	10	5	10	10	10	10	5	4	5	10	--	10	10
	AIR	7	10	10	5	10	10	8	7.8	5	4	5	7.5	--	10	8
D	HAND	7	10	10	7.5	8	10	8	7.5	5	6	5	10	--	10	8
	AIR	7	10	10	7.5	10	10	10	7.2	5	6	5	7.5	--	10	8

NOTE: Final rating for a given alternative is to be determined by combining ratings for hand and air emplaced categories.

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal, maximum, and minimum values of the weighting factors used are given in Table IV-XII.

Table IV-XIII lists the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion. The evaluation scores in this table are accurate to two significant figures. The last line is the evaluation rating or weighted score for each alternative. Note that Table IV-XIII is somewhat different from Table IV-XII. The criteria are listed in a different order on Table IV-XII which has no impact on the results. The Spectrum Utilization and Energy Requirements criteria were eliminated from Table IV-XIII as they are major criteria that do not have any impact on differentiating between alternatives. They can be eliminated from the analysis without changing the results. The evaluation scores for the Hand and Air versions of each alternative were averaged to produce one evaluation score for each alternative under each criterion.

To illustrate how each value listed in the evaluation rating line was obtained, a sample calculation for one of the alternatives using additive weighting is presented. Consider Alternative A of Table IV-XIII. The weighting factor for Physical Characteristics - Size (.3275) and the relative score for Size (9) were multiplied. Similar products were formed for Weight and Shape. The resultant products were added and the sum multiplied by the Physical Characteristics weight (.1380) producing the overall Physical Characteristics weighted score. Similar calculations were performed for each of the other major criteria. The major criterion overall weighted scores were added with the sum appearing in the last column under evaluation rating. That is the total weighted score for Alternative A using the additive weighting technique.

The calculations described above are given below for illustrative purposes:

$$\begin{aligned}
9.14 = {} & [.1380]\ [(.3275)(9) + (.3575)(10) + (.3200)(9)] \\
& + [.1414]\ [10] \\
& + [.1010]\ [7.8] \\
& + [.1178]\ [(.3325)(10) + (.3700)(10 + (.2975)(10)] \\
& + [.1044]\ [7.5] \\
& + [.1987]\ [10] \\
& + [.1987]\ [(.2625)(10) + (.4375)(8) + (.3000)(8)]
\end{aligned}$$

This initial analysis results in the following preference listing of alternatives.

RANK	ALTERNATIVE	EVALUATION RATING
1	ONE CONFIGURATION - STANDARD ELECTRONICS	9.14
2	SEPARATE CONFIGURATION - COMMON ELECTRONICS	8.37
3	ONE CONFIGURATION - UNIQUE ELECTRONICS	8.03
4	SEPARATE CONFIGURATION - UNIQUE ELECTRONICS	8.07

TABLE IV - XII

WEIGHTING FACTORS

		NOMINAL WEIGHT MAJOR FACTOR	NOMINAL WEIGHT SUB FACTOR	WEIGHT RANGE MIN-IMUM	WEIGHT RANGE MAX-IMUM
I	PHYSICAL	.1380		.0909	.2694
	1 Size		.3275		
	2 Weight		.3575		
	3 Shape		.3200		
II	VERSATILITY	.1414		.0875	.2761
III	HUMAN FACTORS	.1010		.0539	.1582
IV	LOGISTICS	.1178		.0539	.2020
	1 Test Equipment		.3325		
	2 Repair Parts		.3700		
	3 Maintenance Skills		.2975		
V	SCHEDULE	.1044		.0808	.2357
VI	RELIABILITY	.1987		.1178	.3872
VII	COST	.1987		.1347	.3367
	1 R & D		.2625		
	2 Acquistion		.4375		
	3 Support		.3000		

TABLE IV-XIII

EVALUATION SCORES

CRITERIA	ALTERNATIVES			
	A	B	C	D
I. PHYSICAL CHARACTERISTICS (.1380)				
1. Size (.3275)	9	9	10	9
2. Weight (.3575)	10	10	10	10
3. Shape (.3200)	9	10	9	9
II. VERSATILITY (.1414)	10	7.5	5	7.5
III. HUMAN FACTORS (.1010)	7.8	8.8	8.9	7.5
IV. LOGISTICS (.1178)				
1. Test Equipment (.3325)	10	9	5	5
2. Repair Parts (.3700)	10	8	4	6
3. Maintenance Skills (.2975)	10	9	5	5
V. SCHEDULE (.1044)	7.5	7.5	8.8	8.8
VI. RELIABILITY (.1987)	10	8	9	8
VII. COST (.1987)				
1. R&D (.2625)	10	10	7	7
2. Acquisition (.4375)	8	8	10	10
3. Support (.3000)	8	8	10	10
EVALUATION RATING	9.14	8.37	8.03	8.07

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

7.2 Secondary Ranking Techniques. The procedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section are applicable.

The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Table IV-XIV.

7.3 Comparison of Results - Nominal Values. From Table IV-XIV the One Configuration - Standard Electronics alternative is clearly ranked first. The Separate Configuration - Standard Electronics alternative appears to be second although it does rank third in the Logarithmic case. The two unique alternatives are least preferred and sometimes change ranks.

TABLE IV-XIV

ALTERNATIVE EVALUATION RATINGS FOR THE FOUR ANALYTICAL TECHNIQUES USING NOMINAL VALUES

ALTER-	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
NATIVE	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
A	9.14	1	9.20	1	9.09	1	9.45	1
B	8.37	2	8.41	2	8.34	2	8.64	3
C	8.03	4	8.27	3	7.73	4	8.90	2
D	8.07	3	8.18	4	7.94	3	8.63	4

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

8.0 SENSITIVITY ANALYSIS

The procedures and discussions presented in Section III, paragraph 8.0 apply equally to this section except that the basic data presented in this section is applicable.

8.1 Sensitivity Study using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 14 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 7 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately.

The results of the additive weighting sensitivity study are plotted in Figure 4-1. The figure shows that Alternative A is clearly the most preferred. Alternative B ranks second but is close to Alternative C and D which are co-ranked last.

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 60 sensitivity runs, including the additive nominal reference were made for the analysis.

Tables IV-XV through IV-XXI show the computational results from the processing. These results contain the final Evaluation Rating and Rank order as the criterion weighting factors were varied in four techniques.

The relationships among the evaluation scores for each alternative, the nominal weighting factors for the subcriteria and for the major criteria are shown in Table IV-XII. Table IV-XII additionally includes the maximum and minimum values for the major criteria.

In all runs the One Configuration - Standard Electronics alternative is ranked first. Its score is substantially above the second ranked alternative. Other ranks change during the sensitivity study and a summary of the changes are shown in Table IV-XXII (This includes nominal results).

It is obvious from Table IV-XXII that the One Configuration - Standard Electronics is the most preferred alternative. The Separate Configuration - Common Electronics alternative is ranked second. The distinction between the remaining two alternatives is not quite as clear, but this is not all that important as they are both less preferred than the previous two.

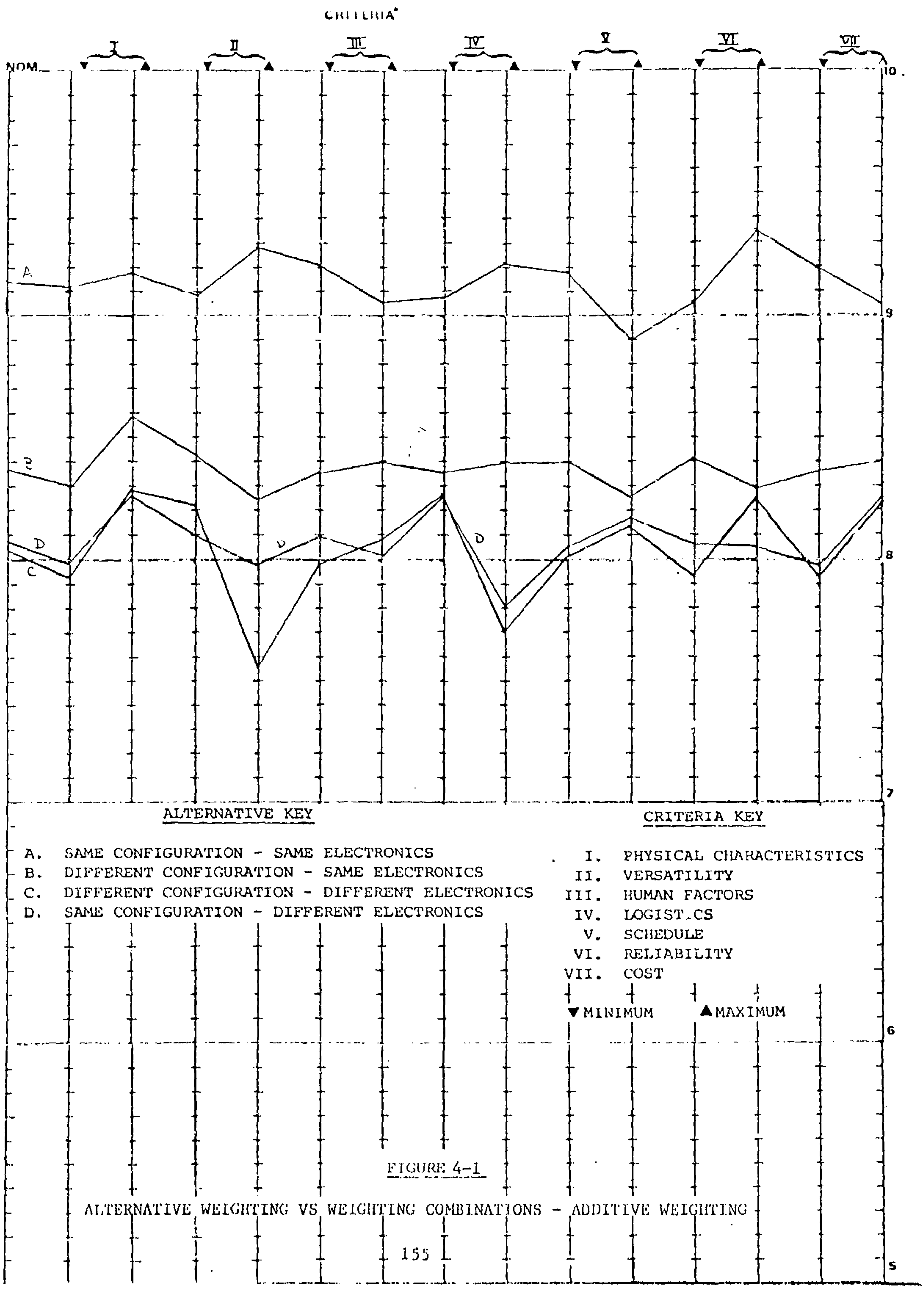


FIGURE 4-1

ALTERNATIVE WEIGHTING VS WEIGHTING COMBINATIONS - ADDITIVE WEIGHTING

TABLE IV - XV

RATINGS OF ALTERNATIVES VS PHYSICAL CHARACTERISTICS

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PHYS								
A	9.13	1	9.19	1	9.07	1	9.45	1
B	8.30	2	8.34	2	8.27	2	8.55	4
C	7.93	4	8.19	3	7.63	4	8.84	2
D	7.99	3	8.11	4	7.87	3	8.57	3
MAX PHYS								
A	9.18	1	9.53	1	9.14	1	9.45	1
B	8.58	2	8.62	2	8.55	2	8.88	3
C	8.29	3	8.51	3	8.01	4	9.07	2
D	8.27	4	8.48	4	8.16	3	8.79	4

WEIGHTS USED IN THESE RUNS

MIN PHYS: PHYS = .0909, VERS = .1491, H F = .1065, LOG = .1242,
SCHD = .1101, REL = .2096, COST = .2096,

MAX PHYS: PHYS = .2694, VERS = .1198, H F = .0856, LOG = .0998,
SCHD = .0885, REL = .1684, COST = .1684,

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

TABLE IV - XVI

RATINGS OF ALTERNATIVES VS VERSATILITY

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN VERS								
A	9.09	1	9.14	1	9.03	1	9.40	1
B	8.43	2	8.47	2	8.40	2	8.69	3
C	8.22	3	8.43	3	7.94	4	8.99	2
D	8.10	4	8.22	4	7.97	3	8.68	4
MAX VERS								
A	9.28	1	9.33	1	9.23	1	9.55	1
B	8.24	2	8.28	2	8.20	2	8.51	3
C	7.55	4	7.85	4	7.22	4	8.67	2
D	7.98	3	8.08	3	7.87	3	8.50	4

WEIGHTS USED IN THESE RUNS

MIN VERS: PHYS = .1467; VERS = .0875; H F = .1073; LOG = .1252;
SCHD = .1110; REL = .2112; COST = .2112;

MAX VERS: PHYS = .1164; VERS = .2761; H F = .0852; LOG = .0993;
SCHD = .0880; REL = .1675; COST = .1675;

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

TABLE IV - XVII

RATINGS OF ALTERNATIVES VS HUMAN FACTORS

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN H F								
A	9.21	1	9.26	1	9.16	1	9.50	1
B	8.35	2	8.39	2	8.32	2	8.63	4
C	7.98	4	8.24	3	7.67	4	8.90	2
D	8.10	3	8.22	4	7.98	3	8.67	3
MAX H F								
A	9.06	1	9.11	1	9.00	1	9.38	1
B	8.40	2	8.44	2	8.37	2	8.65	3
C	8.08	3	8.31	3	7.80	4	8.90	2
D	8.02	4	8.13	4	7.90	3	8.57	4

WEIGHTS USED IN THESE RUNS

MIN H F : PHYS = .1452; VERS = .1488; H F = .0539; LOG = .1240;
SCHD = .1099; REL = .2091; CNST = .2091;

MAX H F : PHYS = .1292; VERS = .1324; H F = .1587; LOG = .1103;
SCHD = .0978; REL = .1861; CNST = .1861;

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

TABLE IV - XVIII

RATINGS OF ALTERNATIVES VS LOGISTICS

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN LOG								
A	9.08	1	9.14	1	9.03	1	9.40	1
B	8.36	2	8.40	3	8.32	2	8.64	4
C	8.27	3	8.47	2	8.02	4	9.00	2
D	8.26	4	8.35	4	8.17	3	8.72	3
MAX LOG								
A	9.22	1	9.28	1	9.17	1	9.51	1
B	8.40	2	8.43	2	8.37	2	8.65	3
C	7.70	4	8.00	3	7.36	4	8.77	2
D	7.81	3	7.96	4	7.65	3	8.50	4

WEIGHTS USED IN THESE RUNS

MIN LOG : PHYS = .1480; VERS = .1516; H F = .1083; LOG = .0539;
SCHD = .1120; REL = .2131; COST = .2131;

MAX LOG : PHYS = .1248; VERS = .1279; H F = .0914; LOG = .2020;
SCHD = .0944; REL = .1797; COST = .1797;

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

TABLE IV - XIX

RATINGS OF ALTERNATIVES VS DEVELOPMENT SCHEDULE/RISK

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN SCHD								
A	9.18	1	9.24	1	9.13	1	9.47	1
B	8.40	2	8.44	2	8.36	2	8.66	3
C	8.01	4	8.26	3	7.70	4	8.91	2
D	8.05	3	8.17	4	7.92	3	8.63	4
MAX SCHD								
A	8.90	1	8.97	1	8.84	1	9.28	1
B	8.25	2	8.29	3	8.21	2	8.52	4
C	8.13	4	8.34	2	7.87	4	8.88	2
D	8.17	3	8.27	4	8.06	3	8.65	3

WEIGHTS USED IN THESE RUNS

MIN SCHD: PHYS = .1416; VERS = .1451; H F = .1037; LOG = .1209;
SCHD = .0808; REL = .2039; CHST = .2039;

MAX SCHD: PHYS = .1178; VERS = .1207; H F = .0862; LOG = .1005;
SCHD = .2357; REL = .1696; CHST = .1696;

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

TABLE IV - XX

RATINGS OF ALTERNATIVES VS RELIABILITY

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN REL								
A	9.05	1	9.11	1	9.00	1	9.38	1
B	8.41	2	8.45	2	8.38	2	8.69	3
C	7.93	4	8.19	4	7.61	4	8.89	2
D	8.07	3	8.20	3	7.94	3	8.68	4
MAX REL								
A	9.34	1	9.39	1	9.29	1	9.60	1
B	8.29	2	8.32	3	8.26	2	8.51	3
C	8.26	3	8.45	2	8.01	3	8.93	2
D	8.05	4	8.14	4	7.96	4	8.50	4

WEIGHTS USED IN THESE RUNS

MIN REL : PHYS = .1519; VERS = .1557; H F = .1112; LOG = .1297;
SCHD = .1149; REL = .1178; CHST = .2188;

MAX REL : PHYS = .1055; VERS = .1081; H F = .0777; LOG = .0901;
SCHD = .0798; REL = .3872; CHST = .1520;

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

TABLE IV - XXI

RATINGS OF ALTERNATIVES VS COSTS

ALTER- NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN COST								
A	9.19	1	9.24	1	9.14	1	9.49	1
B	8.36	2	8.40	2	8.33	2	8.62	3
C	7.93	4	8.18	3	7.63	4	8.83	2
D	7.98	3	8.08	4	7.86	3	8.51	4
MAX COST								
A	9.04	1	9.09	1	8.98	1	9.36	1
B	8.40	2	8.44	3	8.37	2	8.68	4
C	8.23	4	8.46	2	7.95	4	9.06	2
D	8.26	3	8.39	4	8.13	3	8.86	3

WEIGHTS USED IN THESE RUNS

MIN COST: PHYS = .1490; VERS = .1527; H F = .1091; LOG = .1272;
SCHD = .1127; REL = .2146; COST = .1347;

MAX COST: PHYS = .1142; VERS = .1170; H F = .0836; LOG = .0975;
SCHD = .0864; REL = .1645; COST = .3367;

<u>ALTERNATIVE KEY</u>

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

TABLE IV - XXII

CUMULATIVE RANK FREQUENCY
ALL METHODS

ALT.	MODE	MEAN	1ST	2ND	3RD	4TH
A	1	1.000	60 *	0	0	0
B	2	2.400	0	41 *	14	5
C	4	3.117	0	19	15	26 *
D	3	3.483	0	0	31	29

ALTERNATIVE KEY

A. ONE CONFIGURATION - STANDARD ELECTRONICS
B. SEPARATE CONFIGURATION - COMMON ELECTRONICS
C. SEPARATE CONFIGURATION - UNIQUE ELECTRONICS
D. ONE CONFIGURATION - UNIQUE ELECTRONICS

9.0 CONCLUSION

Of the alternatives considered, the one which uses a single configuration with common electronics received the highest ranking by a reasonable margin. All weighting techniques used in the analysis showed similar results. Likewise, a sensitivity analysis with variable weights did not change the ranking of this alternative versus the other alternatives. However, in reviewing the weights which were assigned to the various criteria and subcriteria, the team believes that a disproportionate weight was given to some criteria which tended to favor this alternative over the others. In particular, human factors are believed to be of much greater importance than versatility. Similarly, reliability is given a significantly greater weight in this engineering analysis than others. In view of this, the team does not believe the analysis is conclusive.

10.0 RECOMMENDATION

Based on the above statements, the team recommends a separate configuration with common electronics be used for designing repeaters for air delivered and hand emplaced use (Alternative B).

11.0 SIZE, WEIGHT, SHAPE, AND OTHER PERTINENT DATA

A new air dropped sensor delivery vehicle is being developed by MERDC, designated as the Surface Emplaced Sensor (SES). It appears that a follow-on development along these lines may provide an answer for the air-dropped repeater applications, modifications would have to be made to permit packaging of a repeater as shown in Figure 4-2.

Before preliminary volume calculations pertaining to the SES are made, the advantages and disadvantages of the SES delivery vehicle as a radio repeater will be discussed. Regardless of the deployed location for the radio repeater, two lines of sight must be maintained; one for the sensor link and one for the Receiver/Command-Transmitter link. This requirement implies a canopy hang-up or an antenna deployed 10-20 feet above the ground for proper transmission.

With regard to a SES type delivery vehicle, the above requirements may be difficult to meet. Firstly, the SES is designed to be emplaced on the surface. This may not be ideal for a radio repeater. With the present SES diameter, it may be difficult to store a 10' or 20' antenna into the package. Secondly, the SES is not designed for canopy hang-up. Thirdly, upon deployment of the antenna the SES will tend to be unstable and will perhaps roll. A spike could be implanted automatically to attain stability. The present SES type delivery vehicle does not appear to meet radio repeater requirements with regard to size, weight and packaging requirements.

The SES provides 100 in^3 volume for the electronics and 30 in^3 volume for the batteries. This is a total volume of 130 in^3. As shown in Figure 4-3 the present SES volume is not sufficient for In-band repeaters using alkaline batteries.

The available volume can, of course, be increased by increasing the length of the package. The volumes available in 24", 27" and 30" packages can be found in Figure 4-4. A 30" tube can meet the volume requirements of hybrid and LSI electronics in all cases. There is not sufficient volume, however, for discrete electronics.

The weight requirements of the MN for the HERR using Alternative A (same electronics, same configuration) cannot be met if an in-band alkaline battery, switch-tunable receiver is used (Fig. 4-5). The excess weight, 10 lbs is due primarily to the weight of the alkaline batteries and the presence of the Self Orienting Mechanism (SOM) which is not needed for hand emplacement, but is included since the same equipment is air dropped. In the REMBASS MN, there is no weight restrictions for ADRR.

Figure 4-6 summarizes alternate relay design/power sources and indicates those designs which are potentially suitable for REMBASS from a size and weight viewpoint. The size and weight estimates for relays was taken from a CS&TA Laboratory report entitled, "Sensor Radio Relay," presented to ODDR&E March 73. In some cases maximum use of Hybrid techniques and LSI technology is required. In sizing the batteries, a 60-day life at 0°F was assumed.

AEHPSFE

DIMENSIONS: 21¾ IN. LONG BY 4¼ IN. DIA.
WEIGHT: 20 LBS.
INTERNAL DIAM.: 3.67 IN.

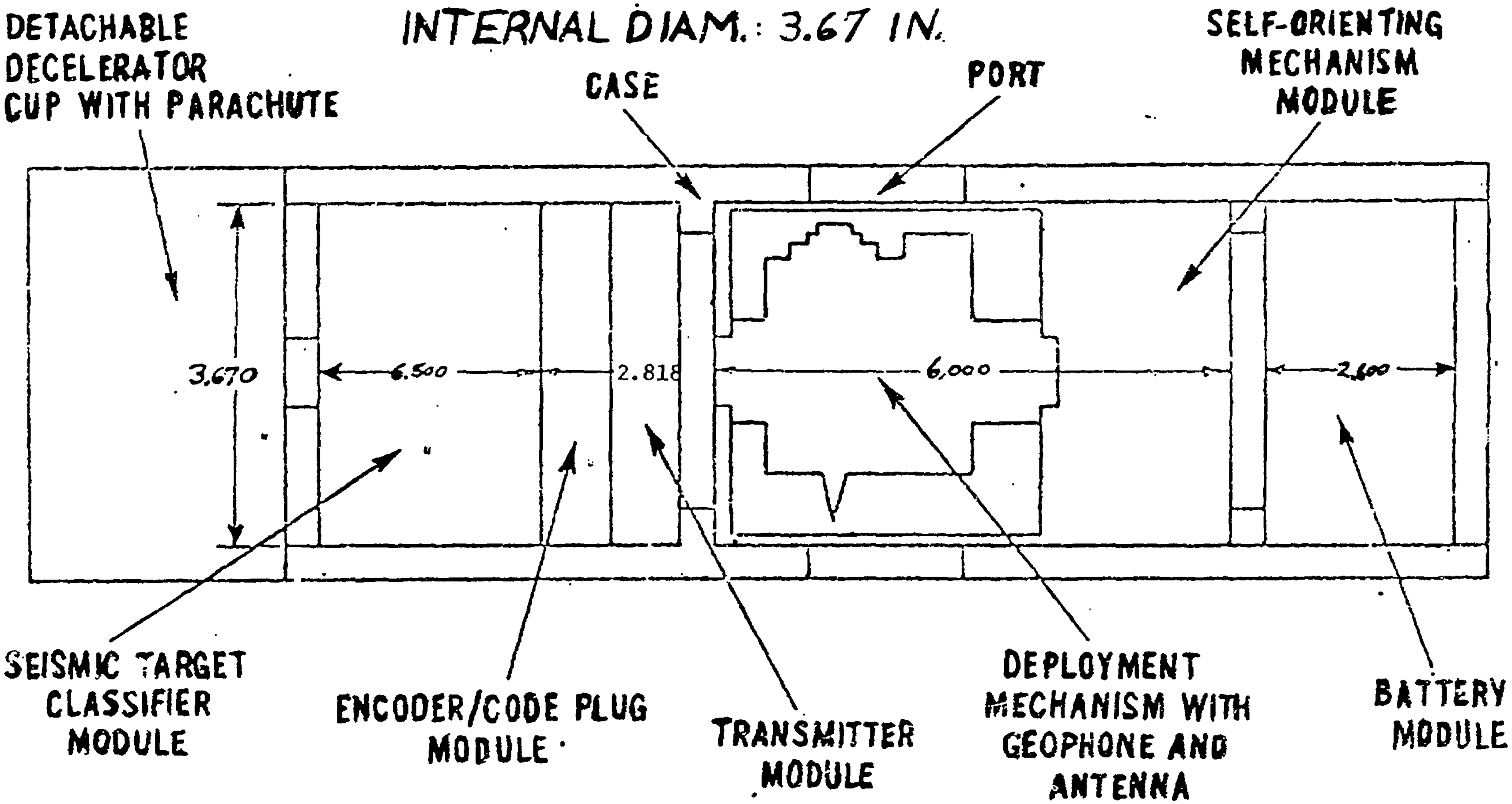


FIGURE 4-2 REPEATER PACKAGING METHOD

REQUIRED ELECTRONIC (LSI) AND BATTERY VOLUME

TYPE BATTERY USED	VOLUME IN^3				
	DIGITAL REPEATER	ANALOG ONLY REPEATER		COMBINED REPEATER	
		IN-BAND	OUT-OF-BAND	IN-BAND	OUT-OF-BAND
Lithium	45	110	55	106	50
Alkaline	111	225	119	219	113

REQUIRED ELECTRONIC (LSI) & BATTERY WEIGHT - HOUSING NOT INCLUDED

TYPE BATTERY USED	WEIGHT LBS				
	DIGITAL REPEATER	ANALOG ONLY REPEATER		COMBINED REPEATER	
		IN-BAND	OUT-OF-BAND	IN-BAND	OUT-OF-BAND
Lithium	7.7	13.5	9.1	9.9	8.1
Alkaline	18.9	34.3	22.3	25.9	20.6

FIGURE 4-3 REPEATER WEIGHT & VOLUME REQUIREMENTS

Present SES - Lengths & Weights

Total Weight -	20.85 lbs	
Tubes & Plugs	7.00 lbs	
Payload	13.85 lbs	
SOM	4.63 lbs	
Battery Electronics	9.22 lbs	
STC	68.7599 in^3	4.6 lbs
E&T	29.8099 in^3	UNK
Battery	27.5038 in^3	2.54 lbs
Total	126.0736 in^3	ADRR space available
SOM removed	189.544 in^3	HERR space available

Available space if increase lengths

SES with SOM	24"	168.38 in^3
No SOM	24"	231.85 in^3
SES with SOM	27"	200.10 in^3
No SOM	27"	263.59 in^3
SES with SOM	30"	231.86 in^3
No SOM	30"	295.33 in^3

FIGURE 4-4 VOLUMES AND WEIGHTS OF PRESENT SES AND PROJECTED VOLUMES IF TUBE LENGTHS ARE INCREASED

Note: Size

If the tube length is increased to 30", its weight will increase 50 percent. Therefore:

Tube weight	10.5 lbs
SOM	4.6 lbs
Total package weight (without electronics or battery)	15.1 lbs
REMBASS overall weight Limit	25.0 lbs
Available payload (electronics and battery	9.9 lbs.

The battery and electronics for the in-band, alkaline battery switch tunable repeater total 13.9 lbs, 10 lbs over the REMBASS MIN limit.

FIGURE 4-5 WEIGHT COMPUTATIONS FOR 30" SES

FIGURE 4-6 - RECEIVERS MEETING REQUIRED MN SPEC FOR VOLUME AND WEIGHT - HAND EMPLACED

Battery	Rec.	Digital	Analog Only		Combined	
			In-Band	Out-of-Band	In-Band	Out-of-Band
Volume - SES - LSI						
Lithium	Fix-Tune	Yes	Yes	Yes	Yes	Yes
	Tunable	Yes	Yes	Yes	Yes	Yes
Alkaline	Fix-Tune	Yes	No*	Yes	No*	Yes
	Tunable	Yes	No*	Yes	No*	Yes
Weight						
Lithium	Fix-Tune	Yes	Yes	Yes	Yes	Yes
	Tunable	Yes	Marginal	Yes	Yes	Yes
Alkaline	Fix-Tune	No+	No+	No+	No+	Yes
	Tunable	No	No	No	No	No

* for 30" Yes

\+ for 30" - Hand Emplaced conditionally yes. Unit overweight by about 10 lbs.

SECTION V

ENGINEERING ANALYSIS 4 - EQUIPMENT CONSTRUCTION METHODS

1.0 SUMMARY

This analysis addresses the design approaches for the transmitter, receiver and logic functions required in the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated against a specific set of criteria; versatility, cost, technical risk, physical characteristics and human factors. The analysis concludes that the common functional module alternative is most preferred. The common use circuits with sub-functional modules alternative was rated a close second, and an attempt will be made to incorporate this idea, where feasible, with common modules.

2.0 INTRODUCTION

The REMBASS system is comprised of several major subsystems. Several different alternative DTS designs may be found which satisfy the system operational and functional requirements of REMBASS within certain constraints. In order to determine which DTS subsystem alternative provides the best choice, alternatives are evaluated and analyzed against common criteria and one or more possible alternatives are selected as candidates for final system components.

This report is concerned with design approach alternatives to provide the transmitter, receiver, and logic functions required in the DTS. Three possible alternatives are described and evaluated.

3.0 STATEMENT OF THE PROBLEM

Data transmission reception and processing functions must be performed in most REMBASS equipment components. Some of these are:

1) Non-Commandable Sensors - message formatting and message transmission.

2) Commandable Sensors - command reception, address recognition and command decoding; response message formatting and transmission.

3) Sensor Control Modules (SCMs) - command message reception, address recognition, message decoding; sensor data storage, message formatting and transmission.

4) Repeaters (digital and/or analog) - command and sensor message reception and retransmission, recognition of message type (command or sensor messages). Recognition of command messages addressed to repeaters. Reformatting of messages in digital repeaters. Formatting of messages in response to repeater commands.

5). Universal Command Receiver - sensor message reception, decoding and display.

6). Universal Command Receiver/Transmitter (UCR/Ts) - command message formatting and transmission. Sensor and repeater message reception, decoding, display and output to Computer Processing Units.

Should these functions be performed by: a) uniquely designed equipment components, customized for each application; b) common functional modules to be used wherever the function is required in the REMBASS DTS; or c) by common circuitry or sub-functional modules that are furnished to designers of unique functional equipments or to common functional module designers and fabricators for incorporation in end items?

These three alternatives are defined further in Section 4.0.

4.0 ALTERNATIVES

4.1 Unique Design of DTS End Items (Transmitter, Receiver or Logic Array) for Each Application. In this alternative, producers of sensors, SCM, repeaters, UCRs and UCR/Ts are required to design and develop each item to fulfill the DTS requirements for a specific application. Each item must, of course, satisfy the performance, functional, and other requirements for the DTS. Each designer/producer is not responsible for, nor concerned with, other functionally similar items used in the REMBASS. He must only satisfy the particular environmental and physical requirements, such as size or the power budget, given him in a specification for a particular end item. Thus, for example, DTS components (e.g., transmitter and encoder for use in a hand emplaced sensor) need not be designed to satisfy the size nor severe implant shock or power constraints of DTS components in an air dropped or artillery delivered sensor or an air dropped repeater. This alternative admits use of previously developed circuits and packages of special electronic components that accomplish subfunctions required in receiver, transmitter, or message processing.

4.2 Common Functional Modules. In this alternative, the power, size, weight, shape, and other requirements of DTS components in all REMBASS applications are tabulated and functional modules that satisfy the worst-case constraints or requirements are developed. These modules are used in all equipment elements requiring that particular function. This alternative also recognizes that some functions are always performed together (e.g., the transmitter and the encoder functions and the receiver and decoder functions). It admits of the integration of such coupled use functional modules into "Integrated Transmitter" and "Integrated Receiver" modules. The alternative also admits incorporation of previously developed circuitry and/or sub-functional modules (e.g., a synthesizer circuit or a Temperature Compensated Voltage Controlled Crystal Oscillator (TCVCXO) module).

4.3 Common Use Circuits and Sub-functional Modules. This alternative provides developers/producers of DTS end items (both unique and common module) circuitry some special electronic piece parts or logic chips for use in functional end items. These GFE furnished pieces or circuits may have been developed at considerable R&D costs (e.g., - a synthesizer) or they may represent considerable production start up investment which would otherwise be duplicated in pursuit of alternatives 4.1 or 4.2.

5.0 CRITERIA

Criteria used in the comparative evaluation of the alternatives of this engineering analysis are defined below. In Section 6.0 each alternative is evaluated against these criteria. In performing the final evaluation each criterion is weighted in proportion to its importance as determined from Material Need (MN) requirements or other pertinent facts. In cases where the relative weight of a criterion is not considered exact, a sensitivity analysis will be performed to determine the effects of errors in the weighting factor.

Performance is not ratable criterion in this engineering analysis since, by definition, each alternative satisfies the performance requirements of the application for which it is intended. In satisfying "worst-case" requirements, alternative 4.2 provides greater performance then is actually required for many applications.

5.1 Versatility. This is the ability of a DTS end item to perform the same function in multiple DTS applications, and provide technical benefits and cost savings in system design and operation.

5.2 Costs. Costs for each alternative are estimated on a relative basis to include engineering development (R&D), initial procurement for a 13 Division Army requirement (acquisition), and continued supply and support (life cycle support).

5.2.1 R&D Costs. This is the cost to develop and test a functional equipment item to the point where initial production may begin. Extending the state-of-the-art of a required capability may be required.

5.2.2 Acquisition Costs. This is the cost to procure and stock the required Army units (Division, Battalion, etc.) with the equipment, spare parts, software, etc., for an initial operational capability. Subsequent costs are covered under life cycle support costs.

5.2.3 Life Cycle Support Costs. These are the costs for replenishing consumed items, test equipment, repair parts, support personnel, logistics support management, transportation.

5.2.3.1 Consumption. Replacement cost for consumed items.

5.2.3.2 Test Equipment. The special equipment needed to properly support a given end item in the field.

5.2.3.3 Repair Parts. The number of unique components necessary to support the DTS end item in the field in case of failure or malfunction.

5.2.3.4 Maintenance Skills. The special technical skills required of support personnel in the field.

5.2.3.5 Logistics Support Management. This is the administrative and record keeping effort required to replenish and maintain inventory control over items.

5.2.3.6 Transportation. This is the relative cost of transporting items to using sites and to and from repair facilities.

5.3 Physical Characteristics.

5.3.1 Size. The physical dimensions of an end item which impact on its versatility, or capability of meeting the size requirements of sensors, repeaters, etc.

5.3.2 Weight. Weight can be a significant constraint on DTS components for hand emplaced sensors and repeaters, in terms of meeting MN requirements. The alternatives will be evaluated on the basis of their impact on the final weight of equipments which use these alternatives.

5.3.3 Volume. The volume of the DTS end items determines their ability to be used in multiple applications. It is assumed that configuration is a flexible parameter within a given volume constraint.

5.4 Development Schedule/Risk. Schedule and risk are related criteria and determine the extent of development required and the probability of successfully acquiring DTS end items.

5.5 Human Factors. This criterion concerns the facility or ease of correct assembly and operation of functional end items.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 Versatility. Comparison of alternatives is given in Table V-I.

6.1.1 Alternative 1 (unique functional items). This alternative has the least versatility. Each end item is customized for its intended application, and there is small chance it can be used without adaptation in any other application where its function is needed.

6.1.2 Alternative 2 (common modular items). This alternative provides maximum versatility. Each end item can be used wherever its function is required in REMBASS. A "universal" transmitter and receiver may be possible. Because of the DTS overview required to realize this alternative, it permits incorporation of desirable features such as the shared use of a synthesizer for a transmitter by a receiver or the elimination of a second receiver for some repeater types. It can also provide substantial relief to the pressing power problem of commandable sensor receivers by reducing the "ON" time to say 10% during which "ON" time a repeatedly transmitted command can be "heard" and responded to.

6.1.3 Alternative 3. Does not effect end item versatility.

6.2 Cost. Comparison of alternatives is given in Table V-II.

6.2.1 Development Costs.

6.2.1.1 Alternative 1. Developmental costs are roughly proportional to the number of unique items that must be developed. Therefore, this alternative has the highest development cost.

6.2.1.2 Alternative 2. By satisfying all application requirements, the common functional module development cost is considerably lower than the sum of development costs of the required unique functional designs of alternative 1. It is expected that in satisfying most case conditions, development costs of these common usage modules may be higher than the development cost of one or more unique modules. But overall, there will be considerable saving over the development of all unique items that perform the same function.

6.2.1.3 Alternative 3. This alternative will reduce development cost of both alternatives 1 and 2 through elimination of duplicative efforts.

6.2.2 Acquisition Cost.

6.2.2.1 Alternative 1. Due to the relatively small production base for each unique design, item overall acquisition costs are expected to be high.

6.2.2.2 Alternative 2. The relatively large production base of each common use functional item will considerably reduce the cost of providing DTS functions in the REMBASS system.

6.2.2.3 Alternative 3. Use of this alternative will significantly reduce acquisition costs of alternative 1, and may decrease the cost of alternative 2.

6.2.3 Life Cycle Support Costs.

6.2.3.1 Consumption.

6.2.3.2 Alternative 1. Items are higher in cost due largely to low production base and therefore they have a higher replacement cost.

6.2.3.3 Alternative 2. Because of the high production base consumption replacement costs will be lowest.

6.2.3.4 Alternative 3. Common piece parts separately procured as GFE for use in alternatives 1 and 2 will reduce the cost of alternatives 1 and 2.

6.2.4 Crew and Personnel.

6.2.4.1 Alternative 1 requires operational and maintenance personnel to become familiar with a much greater number of items requiring considerably more training and skill.

6.2.4.2 Alternative 2 will require operational and maintenance personnel to become familiar with only one of each functional end item reducing the training and skill level required.

6.2.4.3 Alternative 3 reduces the skill and training level for alternative 1, but it will still be greater than required for alternative 2.

6.2.5 Test Equipment.

6.2.5.1 Alternative 1. If a unique approach to developing test equipment is selected, there will be a need for as many test equipments as functionally similar items. Development acquisition, replenishment, and training in use of these equipments will be high.

6.2.5.2 Alternative 2. This alternative minimizes the amount of test equipment required and reduces R&D, acquisition, replenishment and training costs.

6.2.5.3 Alternative 3. This alternative requires special test equipment for the piece parts as well as field test equipment for end items, and therefore maximizes test equipment costs.

6.2.6 Repair Parts.

6.2.6.1 Alternative 1 may require the greatest number of repair parts.

6.2.6.2 Alternative 2 may require fewer repair parts but they, as throw away items, are likely to pose a higher repair cost.

6.2.6.3 Alternative 3 will be comparable to alternative 1.

6.2.7 Intergrated Logistics Management.

6.3.7.1 Alternative 1. Has the greatest number of items and parts to be managed.

6.2.7.2 Alternative 2. Reduces to a minimum the number of end items to be managed.

6.2.7.3 Alternative 3. This alternative increases slightly the number of special piece parts that must be provided and inventoried for alternatives 1 and 2.

6.2.8 Transportation.

6.2.8.1 Alternative 1. Probably will incur greater transportation costs to support sensors. Each item will require a minimum inventory level and, if maintainable, a larger overall float will be required to support all items. Overall weight of units will be greater than alternative 2.

6.2.8.2 Alternative 2. The unit transportation cost and the inventory level and maintenance float can probably be smaller to support the same quantity of sensors and other applications in the DTS, resulting in smaller transportation costs for this alternative.

6.2.8.3 Alternative 3. This alternative does not impact on transportation costs.

6.3 Development Risk. Comparison of alternatives is given in Table V-III.

6.3.1 Alternative 1. Development risk varies with application. Half of applications will pose some development risk.

6.3.2 Alternative 2. Since it must satisfy worst case applications, this alternative has a greater development risk than some functional items of unique design that do not pose worst case constraints.

6.3.3 Alternative 3. By furnishing developed items that have resulted from considerable development investment, this alternative tends to reduce the risk involved in pursuing alternatives 1 and 2.

6.4. Physical Characteristics. Comparison of alternatives is given in Table V-IV.

6.4.1 Alternative 1. Each unique item will be as large and configured as required for its intended application.

6.4.2 Alternative 2. The size, shape, and volume will be determined after the worst case constraints have been defined. Items will be smaller than some unique designs of alternative 1.

6.4.3 Alternative 3. The size and shape of alternatives 1 and 2 will be affected to some degree by the special electronic posts furnished under this alternative. However, by definition, each of these alternatives will satisfy intended unique or worst case requirements respectively.

6.5 Human Factors. Comparison of alternatives is given in Table V-V.

6.5.1 Alternative 1 presents the greatest opportunities for assembly and operating errors.

6.5.2 Alternative 2 minimizes the chances of errors in assembly and use of functional DTS component end items.

6.5.3 Alternative 3 tends to reduce the probability of error in alternative 1.

6.6 The evaluations of the alternatives against the rating criteria is shown in table V-VI.

TABLE V-1

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING VERSABILITITY FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN VERS								
A	5.85	3	6.81	3	4.17	3	8.21	3
B	9.48	1	9.53	1	9.42	1	9.71	1
C	9.25	2	9.37	2	9.07	2	9.65	2
MAX VERS								
A	5.21	3	6.36	3	3.45	3	8.01	3
B	9.55	1	9.59	1	9.50	1	9.75	1
C	9.34	2	9.45	2	9.19	2	9.71	2

WEIGHTS USED IN THESE RUNS

MIN VERS: VERS = .2400, COST = .2322, RISK = .1689, PHYS = .2006, H F = .1583,

MAX VERS: VERS = .3400, COST = .2017, RISK = .1467, PHYS = .1742, H F = .1375,

ALTERNATIVE KEY

A. UNIQUE DESIGN OF DTS END ITEMS
B. COMMON FUNCTION MODULES
C. COMMON USE CIRCUITS & SUB-FUNCTIONAL MODULES

TABLE V-II

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING COST FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN COST								
A	5.65	3	6.70	3	3.87	3	8.20	3
B	9.53	1	9.58	1	9.45	1	9.73	1
C	9.43	2	9.52	2	9.30	2	9.73	2
MAX COST								
A	5.51	3	6.52	3	3.85	3	8.03	3
B	9.47	1	9.53	1	9.41	1	9.71	1
C	9.05	2	9.20	2	8.83	2	9.59	2

WEIGHTS USED IN THESE RUNS

MIN COST: VERS = .3015, COST = .1600, RISK = .1725, PHYS = .2046,
H F = .1615,

MAX COST: VERS = .2041, COST = .3200, RISK = .1395, PHYS = .1656,
H F = .1508,

ALTERNATIVE KEY

A. UNIQUE DESIGN OF DTS END ITEMS
B. COMMON FUNCTION MODULES
C. COMMON USE CIRCUITS & SUB-FUNCTIONAL MODULES

TABLE V-III

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING
DEVELOPMENT SCHEDULE/RISK FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN RISK								
A	5.51	3	6.58	3	3.77	3	8.14	3
B	9.56	1	9.61	1	9.51	1	9.76	1
C	9.26	2	9.38	2	9.09	2	9.66	2
MAX RISK								
A	5.80	3	6.26	3	4.11	3	8.13	3
B	9.38	1	9.44	2	9.32	1	9.64	2
C	9.34	2	9.45	1	9.19	2	9.71	1

WEIGHTS USED IN THESE RUNS

MIN RISK: VERS = .2900, COST = .2279, RISK = .1300, PHYS = .1968,
H F = .1554,

MAX RISK: VERS = .2567, COST = .2017, RISK = .2300, PHYS = .1742,
H F = .1379,

ALTERNATIVE KEY

A. UNIQUE DESIGN OF DTS END ITEMS
B. COMMON FUNCTION MODULES
C. COMMON USE CIRCUITS & SUB-FUNCTIONAL MODULES

TABLE V-IV

OVERALL SCORES AND RANKS USING WEIGHTS
CHANGING PHYSICAL CHARACTERISTICS FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PHYS								
A	5.44	3	6.08	3	3.73	3	7.99	3
B	9.49	1	9.54	1	9.43	1	9.71	1
C	9.26	2	9.38	2	9.09	2	9.66	2
MAX PHYS								
A	5.87	3	6.89	3	4.10	3	8.35	3
B	9.54	1	9.58	1	9.49	1	9.74	1
C	9.33	2	9.44	2	9.17	2	9.70	2

WEIGHTS USED IN THESE RUNS

MIN PHYS: VERS = .2904; COST = .2281; RISK = .1659; PHYS = .1600;
H F = .1556;

MAX PHYS: VERS = .2627; COST = .2064; RISK = .1501; PHYS = .2400;
H F = .1407;

ALTERNATIVE KEY

A. UNIQUE DESIGN OF DTS END ITEMS
B. COMMON FUNCTION MODULES
C. COMMON USE CIRCUITS & SUB-FUNCTIONAL MODULES

TABLE V-V

OVERALL SCORES AND RANKS USING WEIGHTS
CHANGING HUMAN FACTORS

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN H F								
A	5.55	3	6.62	3	3.78	3	8.16	3
B	9.49	1	9.54	1	9.43	1	9.71	1
C	9.29	2	9.31	2	9.13	2	9.69	2
MAX H F								
A	5.70	3	6.66	3	4.03	3	8.08	3
B	9.54	1	9.59	1	9.49	1	9.75	1
C	9.26	2	9.37	2	9.11	2	9.64	2

WEIGHTS USED IN THESE RUNS.

MIN H F : VERS = .2899; COST = .2278; RISK = .1656; PHYS = .1967;
H F = .1200;

MAX H F : VERS = .2602; COST = .2045; RISK = .1487; PHYS = .1766;
H F = .2100;

ALTERNATIVE KEY

A. UNIQUE DESIGN OF DTS END ITEMS
B. COMMON FUNCTION MODULES
C. COMMON USE CIRCUITS & SUB-FUNCTIONAL MODULES

TABLE V-VI

EVALUATIONS OF THE ALTERNATIVES AGAINST RATING CRITERIA

Alternative	Versatility	Dev. Cost	Acquisition Cost	Consumption	Crew/ Personnel	Test Equip.	Repair Parts	Transp	ILMS	Dev. Risk	Phys. Char.	Human Factors
1	1	1	7	2	2	5	10	6	3	6-10	10	7
2	10	8	10	8	10	10	5	10	10	8	10	10
3	10	10	6	10	10	3	10	6	9	10	10	9

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, Paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III, paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal, maximum, and minimum values of the weighting factors used are given in Table V-VII. Table V-VIII lists the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion.

This initial analysis results in the following preference listing of the alternatives.

RANK	ALTERNATIVE	EVALUATION RATING
1	COMMON FUNCTION MODULES	9.51
2	COMMON USE CIRCUITS AND SUB-FUNCTIONAL MODULES	9.28
3	UNIQUE DESIGN OF DTS END ITEMS	5.60

Since the least accurate figures in the calculation are accurate to two significant figures, the evaluation rating given here is accurate to two significant figures.

7.2 Secondary Ranking Techniques. The procedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section are applicable. The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Table V-IX.

TABLE V-VII

WEIGHTING FACTORS

		NOMINAL WEIGHT MAJOR FACTOR	NOMINAL WEIGHT SUB FACTOR	WEIGHT RANGE MIN-IMUM	WEIGHT RANGE MAX-IMUM
I	VERSATILITY	.2800		.2400	.3400
II	COST	.2200		.1600	.3200
	1 R&D		.2625		
	2 ACQUISITION		.4125		
	3 CONSUMPTION		.0745		
	4 MAINTENANCE SKILLS		.0542		
	5 TEST EQUIPMENT		.0623		
	6 REPAIR PARTS		.0501		
	7 TRANSPORTATION		.0339		
	8 LOGIC SUPPORT MGNT.		.0501		
III	TECHNICAL RISK	.1600		.1300	.2300
IV	PHYSICAL	.1900		.1600	.2400
V	HUMAN FACTORS	.1500		.1200	.2100

TABLE V-VIII

EVALUATION SCORES

					A	B	C
I	VERSATILITY	.2800			1.0	10.0	10.0
II	COST	.2200			1.0	8.0	10.0
	1	R&D		.2625	7.0	10.0	6.0
	2	ACQUISITION		.4125	7.0	10.0	6.0
	3	CONSUMPTION		.0785	2.0	10.0	10.0
	4	MAINTENANCE SKILLS		.0542	5.0	10.0	3.0
	5	TEST EQUIPMENT		.0623	10.0	5.0	10.0
	6	REPAIR PARTS		.0501	6.0	10.0	6.0
	7	TRANSPORTATION		.0339	3.0	10.0	9.0
	8	LOGIC SUPPORT MGNT.		.0501			
III	TECHNICAL RISK	.1600			8.0	8.0	10.0
IV	PHYSICAL	.1900			10.0	10.0	10.0
V	HUMAN FACTORS	.1500			7.0	10.0	9.0
	EVALUATION RATING				5.60	9.51	9.28

ALTERNATIVE KEY

A. UNIQUE DESIGN OF DTS END ITEMS
B. COMMON FUNCTION MODULES
C. COMMON USE CIRCUITS & SUB-FUNCTIONAL MODULES

TABLE V-IX

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS AND DIFFERENT WEIGHTING TECHNIQUES

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
A	5.60	3	6.64	3	5.86	3	8.10	3
B	9.51	1	9.56	1	9.45	1	9.72	1
C	9.28	2	9.00	2	9.12	2	9.68	2

ALTERNATIVE KEY

A. UNIQUE DESIGN OF DTS END ITEMS
B. COMMON FUNCTION MODULES
C. COMMON USE CIRCUITS & SUB-FUNCTIONAL MODULES

7.3 Comparison of Results - Nominal Values. From Table V-IX, the Common Function Modules and the Common Use Circuits & Sub-Functional Modules alternatives ranked first and second respectively. The evaluation ratings realized for each are relatively close, but the Common Function Modules alternative is clearly indicated as preferred, by a small margin. The Unique Design of DTS End Items alternative is the least preferred by a significant margin. Throughout the analysis, the alternatives maintained constant rank order while emphasis on high or low scores was performed thus supporting the initial results obtained when the additive technique was used.

8.0 SENSITIVITY ANALYSIS

The procedures and discussions presented in Section III, paragraph 8.0 apply equally to this section except that the basic data presented in this section are applicable.

8.1 Sensitivity Study Using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 10 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 5 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately.

The results of the additive weighting sensitivity study are plotted in Figure 5-1. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. An examination of Figure 5-1 reveals that the three alternatives maintained their initial preference rank order throughout the sensitivity study. Thus supporting the results obtained from the initial analysis.

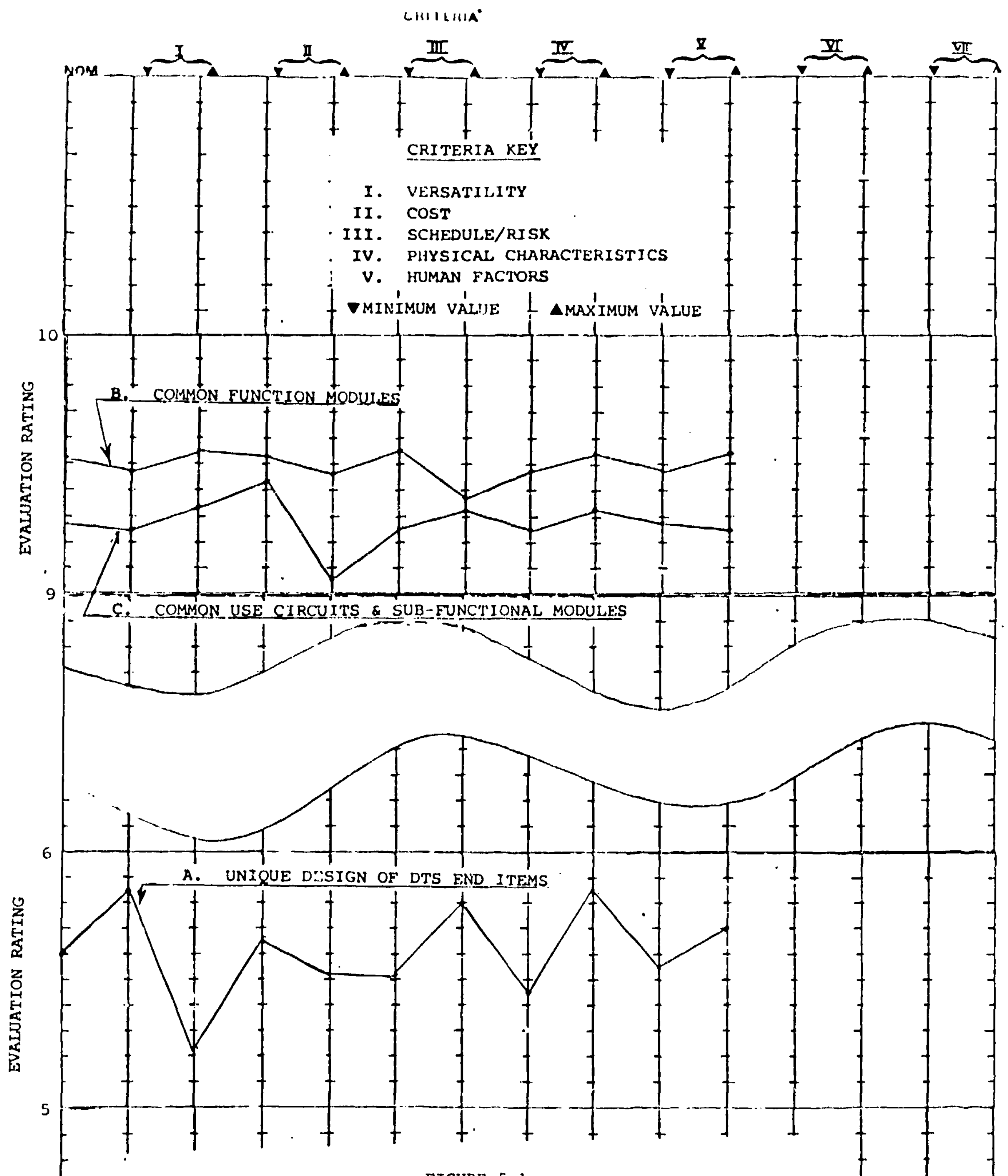


FIGURE 5-1

ALTERNATIVE WEIGHTING VS WEIGHTING COMBINATIONS ADDITIVE WEIGHTING

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 44 sensitivity runs were made for the analysis. These runs showed that the alternative preference rank order remained constant for 42 of the 44 runs. The exceptions occurred when the Schedule/Risk maximum weighting factors were examined using the RMS and the Logarithmic Techniques. For each case, the predominately first two preference ranked alternatives switch ranks. Since the evaluation ratings obtained are close, the switch-over is considered insignificant. The Unique Design of DTS End Items alternative consistantly realized the least preferred rank position. These results are summarized in Table V-X.

From Table V-X the preference rank order of the viable alternatives is as follows:

RANK	ALTERNATIVE
1	COMMON FUNCTION MODULES
2	COMMON USE CIRCUITS & SUB-FUNCTIONS MODULES
3	UNIQUE DESIGN DTS END ITEMS

TABLE V-X

CUMULATIVE RANK FREQUENCY - ALL METHODS

ATT	MODE	MEAN	1ST	2ND	3RD
A	3	3.000	0	0	44 *
B	1	1.045	42 *	2	0
C	2	1.955	2	42	0

ALTERNATIVE KEY

A. UNIQUE DESIGN OF DTS END ITEMS
B. COMMON FUNCTION MODULES
C. COMMON USE CIRCUITS & SUB-FUNCTIONAL MODULES

9.0 CONCLUSION

A common functional modular design ranks significantly higher than a unique design of each hardware element (repeaters, sensors, etc.). The alternative which incorporates common LSI chips as sub-functional units along with common functional modules ranked a very close second. Although the results of the sensitivity analysis did not change the relative ranking of alternatives, it was concluded by the team that the difference in ranking of Alternatives A and B was not significant.

10.0 RECOMMENDATION

In view of the close ranking between alternatives A and B, the team recommends that a common functional modular design be utilized for the hardware elements of the DTS and, in addition, consider using subfunctional units which may have been developed by the Government at the time of contracting for the DTS hardware design. Typical sub-functional units which are being funded in development are the digital synthesizer, and reference oscillator (TCVCXO).

SECTION VI

ENGINEERING ANALYSIS 5-SENSOR CONTROL MODULE

1.0 SUMMARY

This analysis addresses the Sensor Control Module (SCM) and its utility in REMBASS. The alternatives were evaluated against a specific set of criteria; cost, performance, versatility, schedule and logistics. The analysis was inconclusive in that one alternative was not rated higher than the other. The Data Transmission Subsystem (DTS) Team recommended further evaluation on this problem.

2.0 INTRODUCTION

The REMBASS system is composed of several major subsystems. Several different alternative subsystem designs may be found which provide the system operational and functional requirements of REMBASS within certain constraints. In order to determine which subsystem alternative provides the best choice, alternatives are evaluated and analyzed against common criteria and one or more possible alternatives are selected as candidates for final system components.

This engineering analysis is concerned with the relative advantages and disadvantages of employing a SCM with low power (LP) minisensors in the REMBASS system as opposed to using only high power (HP) sensors which have the capability of communicating directly with the receiver or with the repeaters.

3.0 STATEMENT OF THE PROBLEM

Target information must be detected by a sensor and communicated to the readout terminal. Extended ranges or masking terrain features will impose line-of-sight restrictions on a sensor-to-readout terminal RF link. To overcome the RF path restrictions one or more radio repeaters will be required.

In certain tactical situations a higher concentration of sensors in a localized geographical area (i.e., less than 1/2 km radius) may be desired. Coverage of this target area may be accomplished by deploying approximately 6 to 16 HP sensors which report over RF links to the UCR/T or through repeaters to a UCR/T.

This engineering analysis will consider the relative merits of building a REMBASS using only HP sensors or REMBASS using both LP minisensors/SCM's and HP sensors and evaluate these against common criteria.

4.0 ALTERNATIVES

The two alternatives for satisfying the transmission of sensor data are:

1) Through the use of HP sensors only. See Figure 6-1; and 2) through the use of both HP sensors and SCM's with LP minisensors. See Figure 6-2.

FIGURE 6-1
HIGH POWER SENSOR ONLY ALTERNATIVE

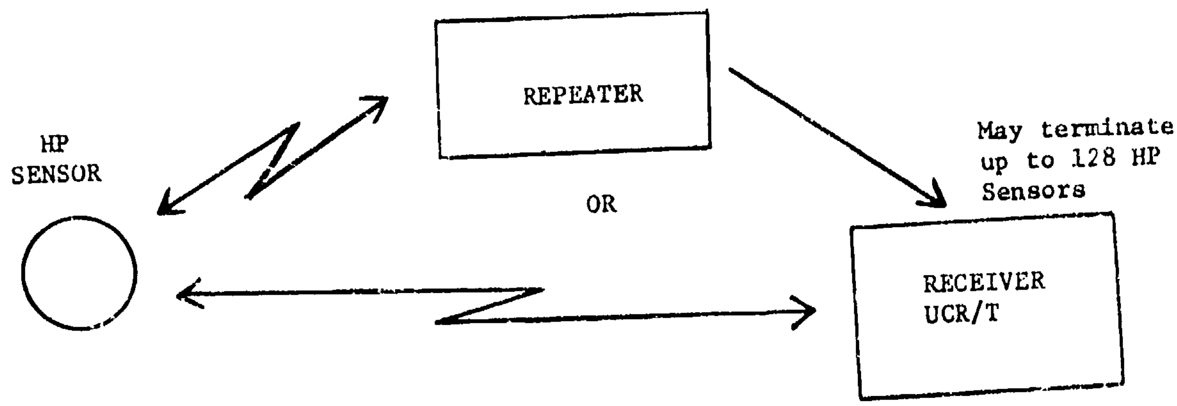
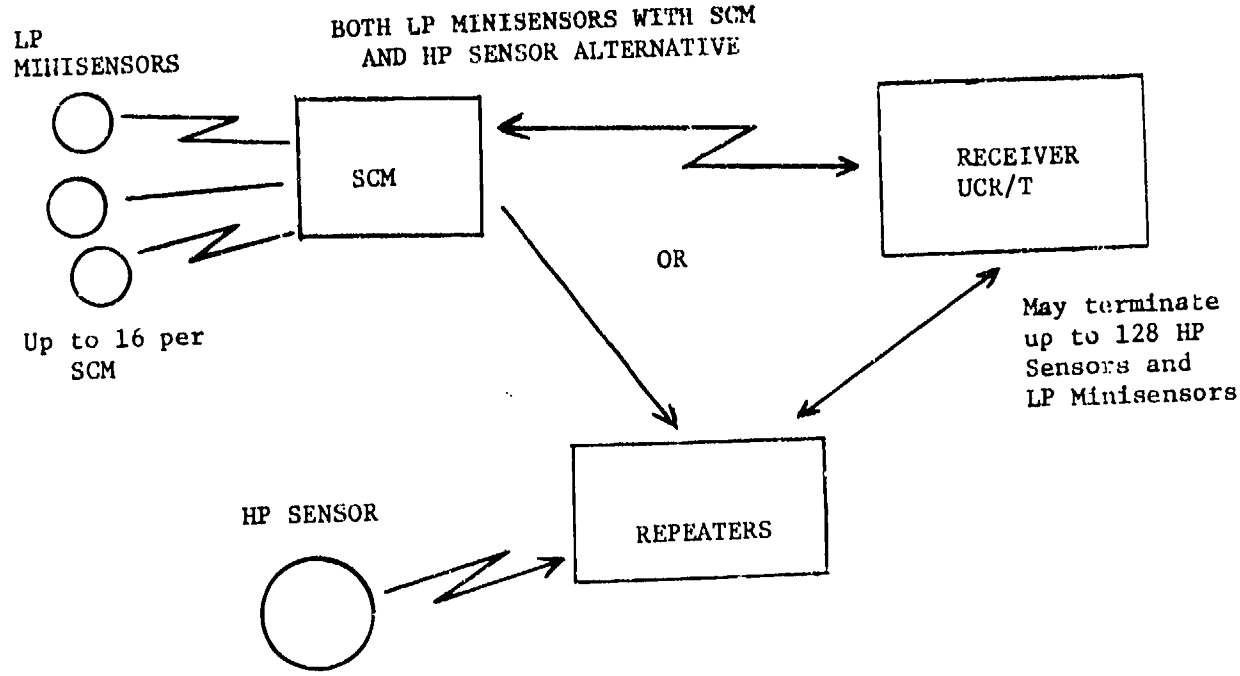


FIGURE 6-2
BOTH LP MINISENSORS WITH SCM AND HP SENSOR ALTERNATIVE



4.1 HP Sensors Only. All sensors would be built with HP transmitters capable of transmitting to the UCR/T or through repeaters to the UCR/T. The HP sensors may be hand emplaced, ballistically emplaced or air dropped. Certain HP sensors may be commandable (i.e., contain a receiver) and may act as classifiers. HP sensors would be used for all tactical deployments requiring sensors.

4.2 Both HP Sensors and SCM/LP Minisensors. Both HP sensors and LP minisensors would be built. LP minisensors and SCM's would be deployed where the tactical situation requires high concentrations of sensors to be deployed. HP sensors would be deployed for other sensor requirements. The HP sensors for this alternative would have the same capabilities as those stated for the HP sensors only alternative. Minisensors have LP transmitters capable of transmitting sensor data over short distances (less than 500 meters) via an RF or wire link solely to sensor control modules.

The minisensor modulation and transmission technique does not have to be identical to other REMBASS components (i.e., HP sensors, repeaters, and UCR/T). By not requiring the same modulation and transmission technique, the minisensors may be built as economically as possible and may even be the same minisensors as those built for the Small Unit Package (e.g., PEWS). Minisensors and SCM's are hand emplaced items. Minisensors are not commandable but the retransmission and processing done by the SCM may be controlled by commands to the SCM. The SCM is capable of handling up to 16 minisensors. The SCM retransmission RF link is compatable with repeaters and UCR/T. NOTE: HP sensors never communicate with the SCM. Certain classification may be accomplished through a combination of minisensor logic and SCM logic/processing. Position location will not be accomplished by the minisensor/SCM subsystem.

5.0 CRITERIA

The criteria which will be used in the compar ive evaluation of the alternatives associated with this engineering analysis are defined below. In paragraph 6.0, each alternative is evaluated against these criteria. Then the alternatives are ranked against each other for each criterion and a relative ranking is presented for each major criterion. This data will be used in paragraph 7.0, to make a comparative analysis of the alternatives to determine which most nearly meets the REMBASS requirements.

5.1 Costs. Costs for each alternative are estimated to include all costs from engineering development, initial purchase and supply of Army elements with components, to the continued resupply of equipments, with supporting costs, for the expected life cycle of the system.

5.1.1 R&D Costs. This is the cost required to develop and test the device up to the point of initial production. This may encompass state-of the-art advances in some instances.

5.1.2 Acquisition Costs. This is the cost required to procure and stock for the Army the equipment, spare parts, software, training, etc. for an initial operational capability. Subsequent costs are covered under life cycle support costs.

5.1.3 Life Cycle Support Costs. These are costs for replacement items, crew and maintenance personnel, ILS (management), transportation, and depot maintenance.

5.2 Performance. Both alternatives will be evaluated against specified performance parameters.

5.2.1 Spectrum Utilized. This criteria relates to the effectiveness with which a particular alternative uses the assigned frequency band.

5.2.2 Vulnerability. The degree of vulnerability to enemy countermeasures associated with each alternative.

5.2.3 Classification Capability. The ability of each alternative to perform classification.

5.3 Versatility.

5.3.1 Ease of Emplacement. The ease of transporting each subsystem considering equipment size and weight and the ease of emplacement.

5.3.2 Ease of Performing Subsystem Checkout. The relative ease of performing subsystem testing and checkout with each alternative.

5.3.2 Subsystem Interoperability. The flexibility to utilize the capabilities of the PEWS sensor for detecting and classifying.

5.4 Schedule and Risk. Consideration is given to development time and the associated risk for each alternative. Development time is the time in months required to perform the engineering development (ED) to a point where production may begin. Relative technical risk of each alternative is considered.

5.5 Logistics. Each alternative is evaluated in terms of maintenance skills, repair parts, and special test equipment required.

5.5.1 Maintenance Skills. The special technical skills required of support personnel in the field.

5.5.2 Repair Parts. The number of unique components necessary to support each alternative subsystem in the field in the event of malfunction.

5.5.3 Test Equipment. Special test equipment needed to properly support each alternative subsystem in the field.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 Costs. Cost information used in this engineering analysis is based on data extracted from the REMBASS Baseline Cost Estimate (BCE) which was based on FY 73 dollars. For the alternative of having no SCM and using only HP sensors, a larger quantity of HP sensors would be required to balance the deletion of LP types. It is that change of quantity which is costed out and compared with the cost of using an SCM. For the alternative using the SCM, costs of the SCM with LP sensors were combined when making comparisons. These RD costs exceeded the HP only alternative, but acquisition and life cycle costs were less. As a further consideration costs of an SCM with PEWS type sensors were examined. For this comparison, the LP acoustic sensor was included to retain the analog capability. However the PEWS sensors are not electrically compatible with REMBASS and the possibility of their use must be ruled out unless a significant PEWS modification program were undertaken.

6.1.1 R&D Costs. The R&D cost includes development through the ED phase. In-house and contractual costs are included as well as non-recurring investment costs. The R&D cost is less for the HP sensor alternative, as shown in Table VI-I.

6.1.2 Acquisition Costs. This is the cost required to procure and stock the Army elements with the equipment, spare parts, software, etc., for an initial operational capability. Subsequent costs are covered under life cycle costs. The acquisition cost of using all HP sensors is greater than that when using an SCM. (Table VI-II).

6.1.3 Life Cycle Costs. These costs are required for replacement items, support personnel, management, transportation and depot maintenance. Using the SCM and LP minisensors results in a life cycle cost approximately 25% less than the other alternative (Table VI-III).

6.2 Performance (see Table VI-IV).

6.2.1 Spectrum Utilized. For a given message, HP sensors require less RF emission bandwidth within the RF spectrum than minisensors with an SCM. This is due to the more stable oscillators (± 5 ppm instability) which are expected to be used in HP sensors. In contrast, the oscillator instability of minisensors may be as large as ± 40 ppm. However, the transmission range of LP minisensors is very short, less than 1/2 km, and therefore instabilities would not create a great problem. The same allocated communication band would be used by SCM, LP minisensors, and HP sensors.

6.2.2 Vulnerability. The problem of vulnerability to enemy countermeasures is examined from two points of view: a) ease of intercept; and b) ease of jamming. The minisensors would be less susceptible to intercept since their output power is only on the order of 250 W, as compared with HP sensors which have an output power of 4 to 5 W. From the intercept point of view, the minisensors would receive a somewhat higher relative ranking. However, jamming of the LP minisensor transmissions at the SCM receiver is a problem which is more or less like that of the UCR and repeater. LP minisensor transmitter output is low but transmission range is short - less than 1/2 km. Like a repeater, the SCM would have a transmission range of 15 to 30 km. A signal arriving at the UCR would not be much different in level whether it originated from an SCM or a HP sensor. If HP sensors were used exclusively, some would undoubtedly be deployed at a somewhat closer distance to the UCR, affording slight improvement in signal strength. Considering both intercept and jamming, both alternatives would rank the same.

6.2.3 Classification Capability. The overall system problem of classification has been considered in examining degree of classification at the SCM. If PEWS type sensors were employed with an SCM, a two class classifier, personnel or vehicles, is already a feature of the sensor. It should be noted that the PEWS sensors are of two varieties, each containing three types of detection, providing information to logic circuits which perform the classification. To accomplish classification when REMBASS LP sensors are used, two choices exist:

a. Incorporate several modes of detection in one sensor with logic circuitry, as in PEWS. This would add to the cost of an already expensive sensor with no added capability over that of the existing PEWS type (classifying LP sensors are approximately 50% more expensive than detecting types);

b. Employ a similar processing scheme in the SCM which would analyze data from several sensors to make a determination. Once again, the rather expensive LP sensors would be used, and in fact, must be used in multiple. Again, no advantage is gained over PEWS. To extend the classification capability of the simple two-class classifier or to add any additional classification features to PEWS type sensors would increase size and weight beyond presently allowed figures for that type sensor. If additional classification were to be placed in the REMBASS LP sensor, cost and size would be added to an already expensive large unit. Placing classification logic, such as that which might be used in the sensors, in the SCM would not gain anything functionally or in performance.

If additional processing were to be used in the SCM for gaining more information than can be had simply from individual sensors, such as velocity, direction, and count, the processor could be built. However, these parameters would of necessity require the SCM to contain still more information such as position location data for each sensor associated with it. Such quantities of information become out of proportion for a unit the size of an SCM which is also situated near enemy activity. This processing must be located at the SRU.

6.3 Versatility (see Table VI-V).

6.3.1 Ease of Emplacement. To accomplish a given mission, a number of sensors may be assumed (e.g., five, and a comparison made between HP sensors and LP sensors with SCM). While the LP minisensors are lighter and smaller compared with HP sensors, their deployment requires the use of an SCM as well. As a LP minisensor measures approximately 6x4x2 in. and weighs about 2 lbs, 5 units would occupy 240 cu. in., and weight 10 lbs. Adding the weight and size of an SCM, about 7 lbs. and 210 cu. in., this combines to a total weight and volume of 450 cu. in. and 17 lbs. By comparison, 5 typical hand emplaced HP sensors with simple classification would probably exceed these figures by about 50% in weight and about 200% in size. This is based on an estimate of 5 lbs. and 250 cu. in. for a simple HP sensor. The SCM with its sensors would therefore have a slight advantage in terms of ease of emplacement.

6.3.2 Ease of Performing Subsystem Checkout. Some HP sensors will be commandable, which feature can be used to provide self-check of a sensor. However, the LP minisensors have no receiver and are therefore not capable of receiving commands. These sensors could not be self-checked by remote means. A pre-programmed periodic self-check could be used, but there would be somewhat added complexity, power drain, size and cost. After emplacement, either alternative would probably simply depend on reliability rather than a checkout scheme. Checkout prior to emplacement would be in favor of the HP sensor alternative because it does not have the SCM as an additional piece of equipment to test.

6.3.3 Subsystem Interoperability. Although the PEWS sensors are not a part of REMBASS, it would be advantageous from logistics and economics points of view to allow interoperation of PEWS sensors with REMBASS, (i.e., as minisensors). The application of PEWS sensors to REMBASS is not a feasible consideration. The present RF transmission characteristics are not compatible: moduation message format are two significant differences. For this reason, relative ranking of this criterion is rated 5.

6.4 Schedule and Risk. Whether an SCM with LP sensors is employed or not, HP sensors of several types must be used. The utilization of an SCM with LP sensors would require the development and production of additional elements for REMBASS. Although no significant risks world be involved, the aggregate of HP sensors, LP sensors, and SCM would rate a lower ranking for schedule and risk than for HP sensors alone (see Table VI-VI).

6.5 Logistics. Table VI-VII depicts the relative rating for the various factors of logistics.

6.5.1 Maintenance Skills. Similar levels of skill will be required for maintenance of either alternative subsystem.

6.5.2 Repair Parts Required. The SCM alternative will allow a somewhat smaller amount of repair parts for HP sensors, but the SCM and LP minisensors will require the addition of more types of repair parts to inventory.

6.5.3 Test Equipment Required. Use of the SCM with LP minisensors should not require additional test equipment beyond that which is necessary for HP sensors.

6.6 Table VI-VIII is a summary matrix of the evaluation data and Table VI-IX gives a cost analysis.

TABLE VI-I

RELATIVE RANKING FOR ESTIMATED R&D COSTS

Alternative	Estimated R&D Costs	Ranking
H P Sensors	5.46 M	10
Both H P Sensors & SCM/LP Minisensors	8.97 M	7

TABLE VI-II

RELATIVE RANKING FOR ACQUISITION COSTS

Alternative	Acquisition Costs	Ranking
H P Sensors	15.7 M	7
Both H P Sensors & SCM/LP Minisensors	10 M	10

TABLE VI-III

RELATIVE RANKING FOR LIFE CYCLE SUPPORT COSTS

Alternative	Life Cycle Support Costs	Ranking
H P Sensors	35.6 M	7
Both H P Sensors & SCM/LP Minisensors	24.4 M	10

TABLE VI-IV

Relative Ranking for Performance

Alternative	Spectrum Utilized	ECM Vulnerability	Classification Capability
H P Sensors	10	10	10
Both H P Sensors & SCM/LP Minisensors	9	10	8

TABLE VI - V

Relative Ranking for Versatility

Alternative	Ease of Emplacement	Ease of Performing Subsystem Checkout	Subsystem Interoperability
HP Sensors	8	10	0
HP Sensors & SCM/LP Minisensors	10	9	5

TABLE VI - VI

Relative Ranking for Schedule & Risk

Alternative	Schedule & Risk	Relative Ranking.
HP Sensors	10	10
HP Sensors & SCM/LP Minisensors	7	7

TABLE VI - VII

Relative Ranking for Logistics

Alternative	Maintenance Skills	Repair Parts	Test Equipment
HP Sensors	10	10	10
HP Sensors & SCM/LP Minisensors	9	9	9

TABLE VI- VIII

SUMMARY MATRIX OF EVALUATION DATA

Alternatives	Costs			Performance			Versatility				Logistics		
	R&D	Acquisition	Life Cycle Support	Spectrum Utilized	ECM Vulnerability	Classification Capability	Ease of Emplacement	Ease of Performing Subsystem Checkout	Subsystem Interoperability	Schedule & Risk	Maintenance Skills	Repair Parts	Test Equipment
HP Sensors	10	7	7	10	10	10	8	10	0	10	10	10	10
HP Sensors & SCM/LP MINI sensors	7	10	10	9	10	8	10	9	5	7	9	9	9

TABLE - VI - IX

COST ANALYSIS

SCM + LP				SCM + PEWS + LP ACOUSTIC				ADDED HP (NO SCM)			
	RD	ACQ	LC		RD	ACQ	LC		RD	ACQ	LC
SCM	1744.4	1557.2	4176.5	SCM	1744.4	1557.2	4176.5	HPSS	1745.5	7761.1	19,400.0
LPSS	1909.6	4063.6	10151.4	PEWS I	1046.0	474.0	1986.0	HPMS	1710.1	6220.9	15,842.0
LPMS	1869.4	2870.5	6708.5	PEWS II		402.0	1632.0	HPAS	1999.7	1667.2	363.3
LPES	2248.4	1381.6	2977.4	LPAS	1197.2	120.5	363.3		5455.3	15649.2	35,605.3
LPAS	1197.2	120.5	363.3		3987.6	2553.7	8157.8				
	8969.0	9993.4	24377.1								

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III, paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal, maximum, and minimum values of the weighting factors used are given in Table VI-X. Table VI-XI lists the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion. The evaluation scores in this table are accurate to two significant figures. The last column is the evaluation rating or weighted score for each alternative.

7.2 Secondary Ranking Techniques. The procedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section are applicable. The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Table VI-XII.

7.3 Comparison of Results - Nominal Values. From Table VI-XII, Alternatives A and B are ranked so closely (with the exception of the Multiplicative Technique) that no clear difference exists between them. An examination of Tables VI-X and VI-XI indicates that for the three top rated criteria (I,II,III), B outranked A in I and III but was second in criterion II. However, in both remaining criteria, which have a combined rating higher than either, I, II, or III, A outranked B. Therefore, the composite ER values are inconclusive with regard to the selection of a top ranked alternative.

TABLE VI-X.

WEIGHTING FACTORS

		NOMINAL WEIGHT		WEIGHT RANGE	
		MAJOR FACTOR	SUB FACTOR	MIN- IMUM	MAX- IMUM
I	COST	.2500		.1875	.3625
	1 R&D		.2375		
	2 Acquisition		.3500		
	3 Support		.4125		
II	PERFORMANCE	.2500		.1875	.3625
	1 Spectrum Utilization		.3000		
	2 ECM Vulnerability		.4125		
	3 Classification Capability		.2875		
III	VERSATILITY	.2125		.1625	.2875
	1 Ease of Employment		.4125		
	2 Ease of Performing Checkout		.3125		
	3 Subsystem Interchangability		.2750		
IV	SCHEDULE	.1000		.0750	.1875
V	LOGISTICS	.1875		.1500	.2875
	1 Maintenance Skills		.3458		
	2 Repair Parts		.3333		
	3 Test Equipment		.3208		

TABLE VI-XI

EVALUATION SCORES

		A	B
I.	COST (.2500)		
	1. R&D (.2375)	10.0	7.0
	2. Acquisition (.3500)	7.0	10.0
	3. Support (.4125)	7.0	10.0
II.	PERFORMANCE (.2500)		
	1. Spectrum Utilization (.3000)	10.0	9.0
	2. ECM Vulnerability (.4125)	10.0	10.0
	3. Classification Capability (.2875)	10.0	8.0
III.	VERSATILITY (.2125)		
	1. Ease of Employment (.4125)	8.0	10.0
	2. Ease of Performing Checkout (.3125)	10.0	9.0
	3. Subsystem Interchangability (.2750)	.0	5.0
IV.	SCHEDULE (.1000)	10.0	7.0
V.	LOGISTICS (.1875)		
	1. Maintenance Skills (.3458)	10.0	9.0
	2. Repair Parts (.3333)	10.0	9.0
	3. Test Equipment (.3208)	10.0	9.0
	EVALUATION RATING	8.67	8.76

ALTERNATIVE KEY

A- HIGH POWERED SENSORS ONLY
B- BOTH HP SENSORS & SCM/MINISENSORS

TABLE VI-XII

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS
AND DIFFERENT WEIGHTING TECHNIQUES

ALTER-NATIVE	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
A	8.67	2	9.02	1	6.12	2	9.56	1
B	8.76	1	8.87	2	8.62	1	9.23	2

ALTERNATIVE KEY

A- HIGH POWERED SENSORS ONLY
B- BOTH HP SENSORS & SCM/MINISENSORS

8.0 SENSITIVITY ANALYSIS

The procedures and discussions presented in Section III, paragraph 8.0 apply equally to this section except that the basic data presented in this section are applicable.

8.1 Sensitivity Study Using The Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 10 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 5 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately.

The results of the additive weighting sensitivity study are plotted in Figure 6-3. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. An examination of Figure 6-3 reveals that neither alternative clearly ranked first. Alternative A achieved five first place rankings to six for B. Although B also attained a greater ER average than A, the ER margin was not large enough to award B the first place ranking.

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 44 sensitivity runs were made for the analysis. These runs showed that employing the RMS and Logarithmic Techniques, A outranked B in all but one run. However, the ER margin was extremely small and, therefore, not sufficient to declare A as being ranked first. Conversely, employing the multiplicative technique, B significantly outranked A for all runs. The above data is contained in Tables VI-XIII through VI-XVII.

For computer computational purposes, those alternatives which received zero valued relative scores were arbitrarily assigned near zero values. Hence, in Alternative A (HP sensors only), the overall scores shown in the multiplicative column of Tables VI-XIII through VI-XVIIII are in reality zeros.

The summary of all results, Table VI-XVIII for nominal and minimum/maximum weighting factor variations processed via all four calculation techniques, shows no decisive preference for either alternative.

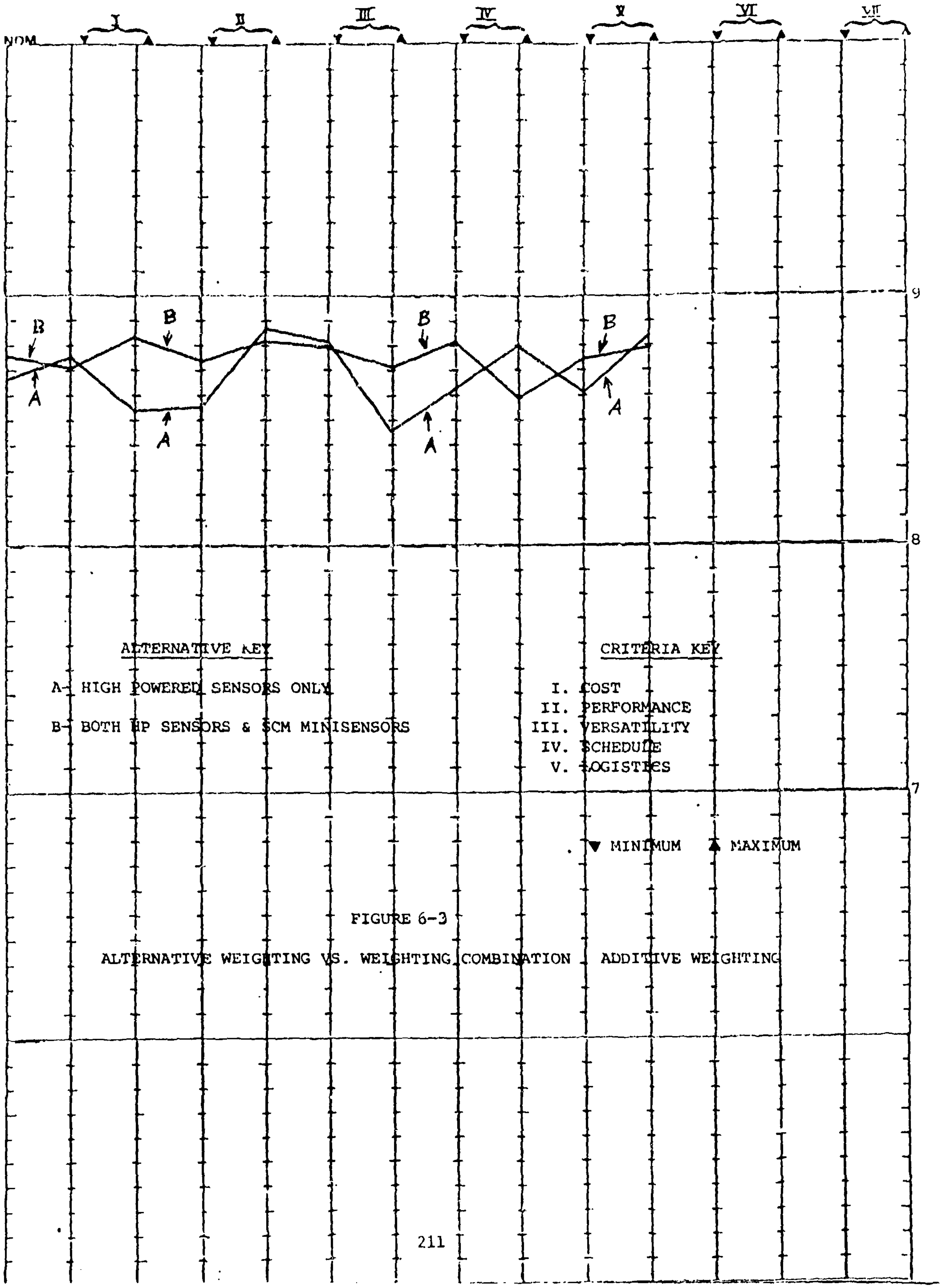


FIGURE 6-3

ALTERNATIVE WEIGHTING VS. WEIGHTING COMBINATION ADDITIVE WEIGHTING

TABLE VI-XIII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING COST FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN COST								
A	8.75	1	9.11	1	6.01	2	9.57	1
B	8.71	2	8.83	2	8.58	1	9.15	2
MAX COST								
A	8.53	2	8.85	2	6.32	2	9.38	1
B	8.80	1	8.95	1	8.71	1	9.37	2

WEIGHTS USED IN THESE RUNS

MIN COST: COST = .1875, PERF = .2708, VERS = .2302, SCHD = .1083, LOG = .2031,

MAX COST: COST = .3625, PERF = .2125, VERS = .1806, SCHD = .0850, LOG = .1594,

ALTERNATIVE KEY

A- HIGH POWERED SENSORS ONLY
B- BOTH HP SENSORS & SCM/MINISENSORS

TABLE VI- XIV

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING PERFORMANCE FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PERF								
A	8.56	2	8.93	1	5.87	2	9.45	1
B	8.73	1	8.84	2	8.59	1	9.22	2
MAX PERF								
A	8.87	1	9.17	1	6.59	2	9.59	1
B	8.81	2	8.91	2	8.69	1	9.25	2

WEIGHTS USED IN THESE RUNS

MIN PERF; COST = .2708; PERF = .1875; VERS = .2302; SCHD = .1083;
LOG = .2031;

MAX PERF; COST = .2125; PERF = .3623; VERS = .1808; SCHD = .0850;
LOG = .1594;

ALTERNATIVE KEY

A- HIGH POWERED SENSORS ONLY
B- BOTH HP SENSORS & SCM/MINISENSORS

TABLE VI-XV

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING VERSATILITY FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN VERS								
A	8.81	1	9.10	1	6.73	2	9.54	1
B	8.79	2	8.89	2	8.66	1	9.23	2
MAX VERS								
A	8.46	2	8.49	1	5.30	2	9.45	1
B	8.71	1	8.44	2	8.56	1	9.23	2

WEIGHTS USED IN THESE RUNS

MIN VERS: COST = .2659, PERF = .2659, VERS = .1625, SCHD = .1063,
LOG = .1994,

MAX VERS: COST = .2262, PERF = .2262, VERS = .2875, SCHD = .0905,
LOG = .1696,

ALTERNATIVE KEY

A- HIGH POWERED SENSORS ONLY
B- BOTH HP SENSORS & SCM/MINISENSORS

TABLE VI-XVI

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING SCHEDULE FACTORS

ALTER- NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN SCHD								
A	8.63	2	8.99	1	8.04	2	9.49	1
B	8.81	1	8.91	2	8.67	1	9.26	2
MAX SCHD								
A	8.80	1	9.12	1	6.42	2	9.56	1
B	8.59	2	8.70	2	8.45	1	9.11	2

WEIGHTS USED IN THESE RUNS

MIN SCHD: COST = .2569, PERF = .2569, VERS = .2184, SCHD = .0750,
LOG = .1927,

MAX SCHD: COST = .2257, PERF = .2257, VERS = .1918, SCHD = .1875,
LOG = .1693,

ALTERNATIVE KEY

A- HIGH POWERED SENSORS ONLY
B- BOTH HP SENSORS & SCM/MINISENSORS

TABLE VI-XVII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING LOGISTIC FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN LOG								
A	8.61	2	8.97	1	5.98	2	9.48	1
B	8.75	1	8.86	2	8.61	1	9.24	2
MAX LOG								
A	8.83	1	9.14	1	6.50	2	9.58	1
B	8.79	2	8.88	2	8.67	1	9.20	2

WEIGHTS USED IN THESE RUNS

MIN LOG : COST = .2615, PERF = .2615, VERS = .2223, SCHD = .1046, LOG = .1500,

MAX LOG : COST = .2192, PERF = .2192, VERS = .1863, SCHD = .0877, LOG = .2875,

ALTERNATIVE KEY

A- HIGH POWERED SENSORS ONLY
B- BOTH HP SENSORS & SCM/MINISENSORS

TABLE VI-XVIII

~~CUMULATIVE RANK FREQUENCY~~
ALL METHODS

ALT	MODE	MEAN	1ST	2ND
A	1	1.409	26 *	18
B	2	1.591	18	26

ALTERNATIVE KEY

A- HIGH POWERED SENSORS ONLY
B- BOTH HP SENSORS & SCM/MINISENSORS

9.0 CONCLUSIONS

The relative ranking of the two alternatives, based on the weighted and sensitivity analyses, was not conclusive. This could be due to several factors: a) the alternatives are equally capable of providing the operational requirements; b) the weighting factors applied to the criteria are questionable; or c) the set of evaluation criteria is not sufficient or complete.

10.0 RECOMMENDATIONS

Based on the inconclusive results of the evaluation, no recommendation is made. If the possible use of a SCM with LP mini-sensors is still considered a viable alternative, additional evaluation with other criteria should be considered.

SECTION VII

ENGINEERING ANALYSIS 6
NUMBER OF CHANNELS FOR REPEATER

1.0 SUMMARY

This analysis addresses the number of channels required for each radio repeater that will be used in the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated against a specific set of criteria; cost, physical characteristics, technical risk, performance, logistics, and versatility. The analysis concluded that single channel repeaters consistantly ranked first. The team recommended that the single channel repeaters be developed, and that dual channel repeaters be developed for special applications.

2.0 INTRODUCTION

The REMBASS system is composed of several major subsystems. For each of these subsystems, several different alternative designs are possible which will provide the system operational and functional requirements of REMBASS within certain constraints. It is presumed that one of these alternatives will provide an optimum REMBASS system. To make this choice all alternatives are described, evaluated, and analyzed against common criteria and one or more possible alternatives are selected as candidates for final system evaluation.

This report is concerned with facts related to optimization of the REMBASS repeater and in particular with providing basic information needed to establish the number of channels a repeater should have.

3.0 STATEMENT OF THE PROBLEM

Extended ranges or masking terrain features will impose line-of-sight restrictions on a sensor-to-readout terminal RF link. To overcome the RF path restrictions, one or more radio repeaters will be required.

The tactical situation will frequently require the deployment of two or more sensor fields, and technical considerations will dictate separate RF links (channels) for each field; terrain topology, however, may provide only one location for repeater emplacement. Figure 7-1 depicts two single channel repeaters retransmitting sensor data from two sensor fields. Figure 7-2 shows an alternative solution using one dual channel repeater to retransmit sensor data from the same two sensor fields.

This engineering analysis will consider the relative merits of using all single channel, all dual channel or both single and dual channel repeaters for REMBASS and evaluate these against common criteria.

4.0 ALTERNATIVES

Three alternatives for satisfying the REMBASS repeater requirements are analyzed to determine what type of repeaters are to be built. The three alternatives are:

a) Single Channel Repeaters

b) Dual Channel Repeaters

c) Dual & Single Channel Repeaters

4.1 Single Channel Repeaters. A single channel repeater is capable of retransmitting both commands and sensor data from sensors, sensor control modules, other repeaters, or a command transmitter and contains only one receiving and one transmitting frequency. Additional single channel repeaters would be required to retransmit command and sensor data to and from sensor strings in the event that an additional RF channel for the sensor string is desired to provide greater reliability against enemy jamming. Single channel repeaters may be hand or air emplaced or operated from an airborn platform and may be designed to retransmit either digital, analog, or a mix of both types of data.

4.2 Dual Channel Repeaters. A dual channel repeater is capable of retransmitting commands and sensor data on two RF channels simultaneously. The dual channel repeater is essentially two single channel repeaters packaged in one container. For a REMBASS consisting entirely of dual channel repeaters, a dual channel repeater must be deployed even though only one RF channel is required. The dual channel repeater may be hand or air emplaced, or operated from an airborne platform and may be designed to retransmit either two digital RF channels, two analog RF channels, or one analog and one digital RF channel.

4.3 Dual and Single Channel Repeaters. Both single and dual channel repeaters are built for REMBASS. The capabilities of the repeaters are identical to those stated for the preceding alternatives. This alternative benefits from the operational advantages of using the single or dual channel repeater where best suited, with the principal disadvantage of requiring two types of repeaters to be developed and later maintained in the field.

5.0 CRITERIA

5.1 General. The criteria which will be used in the comparative evaluation of the alternatives associated with this engineering analysis are defined in this section. In paragraph 6.0 each alternative is evaluated against these criteria. Then each alternative is ranked against other alternatives for each criterion and a relative ranking is presented for each major criterion. This data will be used in paragraph 7.0 to make a comparative analysis of the alternatives to determine which most nearly meets the REMBASS requirements.

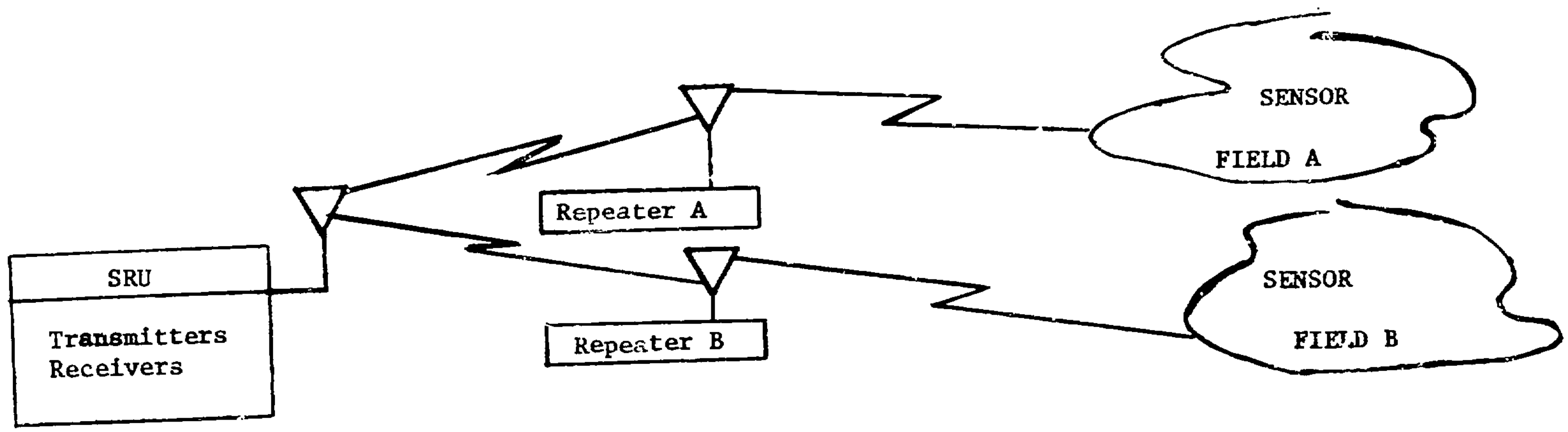


FIGURE 7-1 CO-LOCATED SINGLE - CHANNEL REPEATERS

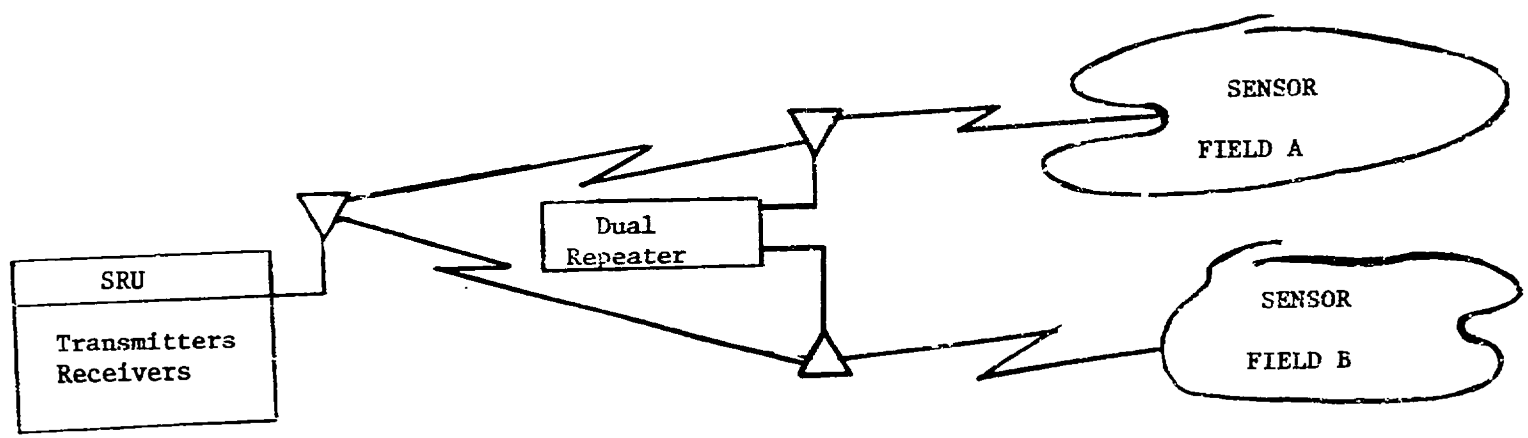


FIGURE 7-2 DUAL-CHANNEL REPEATER

5.2 Costs. Costs for each alternative are estimated to include all costs from engineering development, initial purchase, and supply of each Army element with the required system components, to the continued resupply of equipments, with supporting costs, for the expected life cycle of the system.

5.2.1 R&D Costs. This is the cost required to develop and test the device to the point where initial production may begin. Extending the state-of-the-art of a required capability may be required in some cases.

5.2.2 Acquisition Costs. This is the cost required to procure and stock the required Army elements (Division, Battalion, etc.), with the equipment, spare parts, software, etc., for an initial operational capability. Subsequent costs are covered under life cycle support costs.

5.2.3 Life Cycle Support Costs. These costs are required for replacement items, support personnel, management, transportation, and depot maintenance.

5.3 Physical Characteristics. The physical dimensions of the repeater are critical, not only for hand carrying ability but also because of the requirement to drop repeaters from available aircraft dispensers such as the SUU-42.

5.3.1 Weight. The constraint on weight is a significant criterion for hand emplaced sensors and is limited by the Material Need (MN), to 25 lbs.

5.3.2 Volume. Along with size, the volume of the repeater may determine its ability to be used in certain aircraft dispensers.

5.4 Development Risk. Development risk is estimated to determine the extent of development required and the probability of successfully acquiring a particular repeater alternative.

5.5 Performance.

5.5.1 Receiver Sensitivity. The sensitivity of a receiver for a fixed error rate may be effected by the insertion loss due to the additional filtering required to eliminate transmitter interference inherent in packaging two repeaters in one enclosure. In addition, some receiver desensitization may occur when either transmitter in the package is retransmitting a message.

5.5.2 ECM Vulnerability. This is a measure of the vulnerability of a particular type of repeater to a jamming or countermeasure environment.

5.5.3 Energy Requirements. Since the repeaters will generally be required to operate from batteries, the amount of energy required is a significant criterion for evaluating alternatives.

5.5.4 Spectrum Utilization. This criteria relates to the effectiveness with which a particular alternative uses the assigned frequency band.

5.6 Logistics. The logistics aspect of each alternative is evaluated in terms of the maintenance skills, repair parts, and special test equipment required.

5.6.1 Test Equipment. The special equipment needed to properly support a given repeater in the field.

5.6.2 Repair Parts. The number of unique components necessary to support a repeater in the field in case of failure or malfunction.

5.6.3 Maintenance Skills. The special technical skills required of support personnel in the field.

5.6.4 Equipment Adjustments. The special adjustments required to operate and maintain the equipment.

5.7 Versatility. The versatility criteria is subjective in nature and considers the deployment and operational flexibility of the alternatives.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 General. The MN specifies that both single and dual channel repeaters shall be built. However, the requirements to retransmit one or two RF channels could be satisfied by using any of three alternatives respectively:

Alternative	One RF channel	Two RF channels
a) Single channel	one single channel repeater	two single channel repeaters
b) Dual channel	one dual channel repeater	one dual channel repeater
c) Both	one single channel repeater	one dual channel repeater

This evaluation will consider the criteria which impact on what type of repeaters are to be built.

6.2 Costs. Costs are based on the information provided in the REMBASS "Baseline Cost Estimate" (BCE) dated Feb 1973. The quantity breakout for a 13 division force has been modified to eliminate ballistically emplaced repeaters and apportion the quantity to other type repeaters.

	57 per div.
	x13 divisions
	741
Total Number of	+20% for Training and Pipeline
Repeaters Required	889

Rounded to 900 — 112 dual channel
788 single channel

Of the 900 total repeaters required to be procured, the REMBASS BCE designated 112 as dual channel repeaters and 788 as single channel repeaters. These quantities of single and dual channel repeaters are the basis of the cost estimates for the alternative including both repeaters. A total of 1012 single channel repeaters are required for the all single channel REMBASS alternative. The quantity was obtained by assuming that each dual channel repeater required in the BCE would be replaced by two single channel repeaters. This is found by the following:

(112 DC X 2) + 788SC = 1012 Single Channel Repeaters

A total of 703 dual channel repeaters are required for the all dual channel REMBASS alternative. This quantity was obtained by assuming that half of the single channel repeaters required in the BCE would be replaced by dual channel repeaters on a basis of one dual channel repeater for two single channel repeaters with both channels operational when deployed. The remaining half of the single channel repeaters would be replaced by dual channel repeaters on a one for one basis, on the assumption that a need for retransmitting only one RF channel will exist even though only dual channel repeaters will be built. This is found by the following:

(1/2 788 SC) (1/2) + 1/2 (788 SC) + 112 DC = 703 Dual Channel Repeaters

6.2.1 R&D Costs. R&D costs include the in-house and contractor development costs up to first article production. As shown in Table VII-I, R&D costs for the alternative consisting of both dual and single channel repeaters is most expensive simply because both types of repeaters must be developed.

TABLE VII - I
RELATIVE RANKING FOR ESTIMATED R&D COSTS

Alternative	Estimated R&D Costs*	Ranking
Both Dual & Single Channel 112 + 788 = 900 units	Dual 1,960.8 Single 1,510.1 3,470.9	5
All Single Channel 1012 units	1,510.1	10
All Dual Channel 703 units	1,960.8	8

*Cost in 1,000 dollars

6.2.2 <u>Acquisition Cost</u>. As indicated in Annex B of BCE, the acquisition costs represent hardware, spare and repair parts, training, production engineering, and PMO costs. Table VII-II is a summary of acquisition costs for the various alternatives. As shown, the alternative for all dual channel repeaters is estimated as most expensive primarily because the dual unit costs more than a single channel repeater and the associated costs that comprise the acquisition costs are based on per unit costs.

TABLE VII - II
RELATIVE RANKING FOR ESTIMATED ACQUISITION COSTS

Alternative	Estimated Acquisition Costs*	Ranking
Both Dual & Single Channel 112 + 788 = 900 units	Dual 239.8 Single 896.1 1,135.9	10
All Single Channel 1012 units	1,150.8	10
All Dual Channel 703 units	1,504.9	7.5

*Cost in 1,000 dollars

6.2.3 <u>Life Cycle Support Costs</u>. Life cycle support costs consist of the following: crew and maintenance personnel, consumption/replacement, Integrated Logistic Support (ILS), transportation, and depot maintenance. Table VII-III is a summary of the life cycle support costs for a 10 year life cycle for a 13 division force. An interesting result is that the life cycle support costs for the three alternatives are similar.

TABLE VII-III
RELATIVE RANKING FOR ESTIMATED LIFE CYCLE SUPPORT COSTS

Alternative	Estimated Life Cycle Support Costs *	Ranking
Both Dual & Single Channel 112 + 788 = 900 units	Dual 1,137.1 Single 5,133.9 6,271.0	10
All Single Channel 1012 units	6,593.0	9.2
All Dual Channel 703 units	7,137.1	8.8

*Cost in 1,000 dollars

6.3 Physical Characteristics. Section IV, paragraph 11.0, engineering analysis 3 entitled "Repeater Configuration" lists the total electronic and battery weight, and volume for different types of single channel repeaters. Table VI-IV indicates the estimated range of weights and volumes for the alternative repeater types. Estimates are indicated for repeaters using lithium and also alkaline batteries because of the great difference between the characteristics of the two types of batteries. A dual channel repeater may be built within the limitations on weight and volume imposed by the REMBASS MN if maximum use is made of LSI technology, and lithium batteries are used. If alkaline batteries are used instead of lithium, a dual channel repeater may weigh more than 32 lbs. However, use of either battery in a dual channel repeater would not result in a volume greater than the MN requirements.

TABLE VII- IV
RELATIVE RATING OF WEIGHT AND VOLUME
ESTIMATES FOR REPEATER ALTERNATIVES

Alternative	Volume	Weight	Rating
Single Channel Lithium Alkaline	 45-110 in^3 111-225 in^3	 8-14 lbs 19-34 lbs	 10 5
Dual Channel Lithium Alkaline	 90-220 in^3 222-450 in^3	 16-28 lbs 32-56 lbs	 7 2
Both Lithium Alkaline	Worst Case is same as Dual Channel		 7 2

6.4 Development Risk. While the choice of transmission technique will be the overriding factor determining the amount of risk in building a REMBASS repeater, a relative rating can be applied to dual and single channel repeaters. Table VII-V provides relative rating of immunity to risk for the three alternatives. Ratings are based on extrapolating known technology for the present Phase III single channel repeater into the REMBASS single and dual channel repeaters.

TABLE VII-V
RELATIVE RATING OF IMMUNITY TO DEVELOPMENT RISK

Alternative	Relative Risk Immunity	Rating
Single Channel	minimal	7 - 9
Dual Channel	moderate	5 - 7
Both	apply worst case dual - moderate	5 - 7

6.5 Performance.

6.5.1 Receiver Sensitivity. Due to the added requirement of increased filtering necessary to reduce mutual interference caused by packaging two repeaters in one enclosure, it appears that a reduction of 1 to 3 dB in receiver sensitivity for a fixed error rate may be experienced by a dual channel repeater.

6.5.2 Electronic Countermeasure (ECM) Vulnerability. It is assumed that any enemy ECM targeted against REMBASS repeater would effect both single and dual channel repeaters equally. This is because both repeaters retransmit on RF channels which are equivalent and the repeaters have similar performance.

6.5.3 Energy Requirements. A dual channel repeater will require more battery power than a single channel repeater because it consists of almost two complete single channel repeaters. However, when two single channel repeaters are deployed to replace a dual channel repeater the total battery requirements for the two single units will be slightly greater than that for one dual channel repeater.

6.5.4 Spectrum Utilization. Since the three alternatives compare types of repeaters that may be built, there is no change or savings in spectrum utilization when two single channel repeaters replace one dual channel repeater or vice versa. Table VII-VI indicates the relative performance rankings for sensitivity, vulnerability, energy, and spectrum utilization for the three alternatives. In addition a final relative performance ranking for each alternative is listed.

TABLE VII -VI

RELATIVE PERFORMANCE
RANKS FOR THE REPEATER ALTERNATIVES

Alternate	Sensitivity	ECM Vulnerability	Energy Requirements	Spectrum Utilization
All Single Channel	10	10	9.5	10
All Dual Channel	9/5	10	10	10
Both Repeaters	9/5	10	9.5	10

6.6 Logistics.

6.6.1 Test Equipment Required. It appears that the test equipment requirements for the dual and single channel repeaters would not differ significantly. The minor impact is due primarily to the fact that most test equipment will be of the Go, No-Go type.

6.6.2 Repair Parts Required. Depending on the packaging configuration, the dual channel repeater will require a slightly larger quantity of repair parts, some of which may be unique to the dual channel repeater, such as antenna combiners/preamplifiers.

6.6.3 Maintenance Skills Required. For each category of maintenance, it appears only minor differences in maintenance skill levels will be required for the dual and single channel repeaters.

6.6.4 Equipment Adjustments Required. Negligible equipment adjustments should be required for either the single or dual channel repeaters. Note: A repeater must be designed so that it can satisfactorily operate when colocated with other repeaters. Army experience indicates a mutual interference problem exists whenever communications repeaters are operated in close proximity. This mutual interference problem is similar to the mutual interference referred to earlier when describing the difficulties in packaging the dual channel repeaters. However, the isolation required to eliminate mutual interference is generally easier to obtain by using two separate single channel repeaters. Table VII-VII is a summary of the relative logistics rankings and the relative final rank for each of the three alternatives.

TABLE VII- VII

RELATIVE LOGISTICS
RANKING FOR THE THREE ALTERNATIVE REPEATERS

Alternative	Test Equipment	Repair Parts Required	Maintenance Skills Required	Equipment Adjustments Required
All Single Channel	10	10	10	9.5
All Dual Channel	10	9.5	10	9.0
Both Repeaters	10	9.5	10	9.0

6.7 Versatility. The most versatile alternative is building both single and dual channel repeaters. This alternative permits optimum matching of the type of repeater to the number of RF channels required to be retransmitted at any given location. It is also the most econonical alternative when replacing repeaters that become inoperative or fail to deploy and operate after being air dropped. The all single channel repeater alternative is the next most versatile in that by deploying single units any number of RF channels may be retransmitted. Also individual repeaters may be replaced if they become defective. The only disadvantage is a slight inconvenience when two RF channels are to be retransmitted. This is because two single channel repeaters must be deployed instead of one dual channel repeater. The all dual channel repeater alternative is the least versatile in that the capability to retransmit two RF channels is always deployed even though one RF channel may be required. Also, if one out of the two operating RF channels becomes inoperable, a dual channel repeater must be deployed to replace the single RF channel that became inoperable. Table VII-VIII is the relative versatility ranking for the alternative repeaters.

TABLE VII- VIII

Relative Versatility Ranking of Alternative Repeaters

Alternative	Relative Versatility	Ranking
Single Channel	Slightly less than both	9.5
Dual Channel	Least	7.0
Both	Most	10

TABLE VII - IX

SUMMARY MATRIX OF EVALUATION DATA

CRITERIA

ALTERNATIVES	COSTS			Physical Charac.		Development Risk	Performance				Logistics				Versatility
	R&D	Acquisition	Life Cycle Support	Volume	Weight		Re. Sensitivity	ECM Vulnerability	Energy Reqmts.	Spectrum Utilization	Test Equipment	Repair Parts	Maintenance	Equip. Adjustment	
ALL SINGLE CHANNEL REPEATERS	10	10	9.2	10/5	10/5	7-9	10	10	9.5	10	10	10	10	9.5	9.5
ALL DUAL CHANNEL REPEATERS	8	7.5	8.8	7/2	7/2	5-7	9/5	10	10	10	10	9.5	10	9.0	7.0
BOTH DUAL AND SINGLE CHANNEL REPEATERS	5	10	10	7/2	7/2	5-7	9/5	10	9.5	10	10	9.5	10	9.0	10

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III, paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal, maximum, and minimum values of the weighting factors used are given in Table VII-X.

Tables VII-XI and VII-XII list the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion. The evaluation scores in this table are accurate to two significant figures. The last line is the evaluation rating or weighted score for each alternative.

This initial analysis results in the following preference listing of the alternatives:

(A) For the Lithium Batteries

RANK	ALTERNATIVE	ER
1	All Single Channel Repeaters (A)	9.50
2	Both Dual & Single Channel Repeaters(C)	8.37
3	All Dual Channel Repeaters (B)	7.91

(B) For the Alkaline Batteries

RANK	ALTERNATIVE	ER
1	All Single Channel Repeaters (A)	8.67
2	Both Dual & Single Channel Repeaters(C)	7.54
3	All Dual Channel Repeaters (B)	7.08

Since the least accurate figures in the calculation are accurate to two significant figures, the evaluation rating given here is accurate to two significant figures.

7.2 Secondary Ranking Techniques. The procedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section is applicable. The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Tables VII-XIII and VII-XIV.

7.3 Comparison of Results - Nominal Values. From Table VII-XIII the ER values and alternative rankings showed good agreement between all of the four calculation techniques. Alternative A clearly ranked highest, with C and B second and third, respectively. In addition, a high degree of stability existed for all of the results. From Table VII-XIV, the ER values were directly proportional to those of Table VII-XIII, and the alternative rankings were the same as shown in Table VII-XIII. These results were expected since the data in Tables VII-XI and VII-XII are the same except for Criterion II. In the case of Criterion II, the Table VII-XI data is larger than Table VII-XII data by the same increment for each alternative; therefore, it is obvious that all further analyses would indicate the same results between the data sets. For this reason, all subsequent analyses will consider only the data set for Lithium Batteries.

TABLE VII-X
WEIGHTING FACTORS

CRITERION		NOMINAL RANGE		WEIGHT RANGE	
		MAJOR FACTOR	SUB FACTOR	MINIMUM	MAXIMUM
I.	COST	.2500		.2000	.4167
	1. R&D		.2333		
	2. ACQUISITION		.4167		
	3. LIFE CYCLE SUPPORT		.3500		
II.	PHYSICAL CHARACTERISTICS	.1667		.1333	.3167
	1. VOLUME		.5000		
	2. WEIGHT		.5000		
III.	TECHNICAL RISK	.1667		.1167	.2500
IV.	PERFORMANCE	.2000		.1500	.3000
	1. SENSITIVITY		.1667		
	2. ECM VULNERABILITY		.4000		
	3. ENERGY REQUIREMENTS		.3000		
	4. SPECTRUM UTILIZATION		.1333		
V.	LOGISTICS	.1167		.0833	.1833
	1. TEST EQUIPMENT		.2833		
	2. REPAIR PARTS		.2667		
	3. MAINTENANCE		.2333		
	4. EQUIPMENT ADJUSTMENT		.2167		
VI.	VERSATILITY	.1000		.0667	.1833

TABLE VII-XI

EVALUATION SCORES FOR REPEATERS USING LITHIUM BATTERIES

CRITERION		A	B	C
I.	COST (.2500)			
	1. R&D (.2333)	10.0	8.0	5.0
	2. ACQUISITION (.4167)	10.0	7.5	10.0
	3. LIFE CYCLE SUPPORT (.3500)	9.2	8.8	10.0
II.	PHYSICAL CHARACTERISTICS (.1667)			
	1. VOLUME (.5000)	10.0	7.0	7.0
	2. WEIGHT (.5000)	10.0	7.0	7.0
III.	TECHNICAL RISK (.1667)	8.0	6.0	6.0
IV.	PERFORMANCE (.2000)			
	1. SENSITIVITY (.1667)	10.0	7.0	7.0
	2. ECM VULNERABILITY (.4000)	10.0	10.0	10.0
	3. ENERGY REQUIREMENTS (.3000)	9.5	10.0	9.5
	4. SPECTRUM UTILIZATION (.1333)	10.0	10.0	10.0
V.	LOGISTICS (.1167)			
	1. TEST EQUIPMENT (.2833)	10.0	10.0	10.0
	2. REPAIR PARTS (.2667)	10.0	9.5	9.5
	3. MAINTENANCE (.2333)	10.0	10.0	10.0
	4. EQUIPMENT ADJUSTMENT (.2167)	9.5	9.0	9.0
VI.	VERSATILITY (.1000)	9.5	7.0	10.0
	EVALUATION RATING	9.50	7.91	8.37

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

TABLE VII-XII

EVALUATION SCORES FOR REPEATERS USING ALKALINE BATTERIES

CRITERION

		A	B	C
I.	COST (.2500)			
	1. R&D (.2333)	10.0	8.0	5.0
	2. ACQUISITION (.4167)	10.0	7.5	10.0
	3. LIFE CYCLE SUPPORT (.3500)	9.2	8.8	10.0
II.	PHYSICAL CHARACTERISTICS (.1667)			
	1. VOLUME (.5000)	5.0	2.0	2.0
	2. WEIGHT (.5000)	5.0	2.0	2.0
III.	TECHNICAL RISK (.1667)	8.0	6.0	6.0
IV.	PERFORMANCE (.2000)			
	1. SENSITIVITY (.1667)	10.0	7.0	7.0
	2. ECM VULNERABILITY (.4000)	10.0	10.0	10.0
	3. ENERGY REQUIREMENTS (.3000)	9.5	10.0	9.5
	4. SPECTRUM UTILIZATION (.1333)	10.0	10.0	10.0
V.	LOGISTICS (.1167)			
	1. TEST EQUIPMENT (.2833)	10.0	10.0	10.0
	2. REPAIR PARTS (.2667)	10.0	9.5	9.5
	3. MAINTENANCE (.2333)	10.0	10.0	10.0
	4. EQUIPMENT ADJUSTMENT (.2167)	9.5	9.0	9.0
VI.	VERSATILITY (.1000)	9.5	7.0	10.0
	EVALUATION RATING	8.67	7.08	7.56

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

TABLE VII-XIII

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS AND DIFFERENT WEIGHTING TECHNIQUES FOR REPEATERS USING LITHIUM BATTERIES

ALTERNATIVE	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
A	9.50	1	9.53	1	9.48	1	9.65	1
B	7.91	3	8.44	3	7.79	3	8.61	3
C	8.57	2	8.57	2	8.15	2	9.20	2

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

TABLE VII-XIV

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS AND DIFFERENT WEIGHTING TECHNIQUES FOR REPEATERS USING ALKALINE BATTERIES

ALTER-NATIVE	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
A	8.67	1	8.85	1	8.44	1	9.32	1
B	7.08	3	7.56	3	6.32	3	8.53	3
C	7.54	2	8.12	2	6.62	2	9.14	2

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

8.0 SENSITIVITY ANALYSIS

The procedures and discussions presented in Section III, paragraph 8.0 apply equally to this section except that the basic data presented in this section are applicable.

8.1 Sensitivity Study Using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 12 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 6 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately. The results of the additive weighting sensitivity study are plotted in Figure 7-3. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. An examination of Figure 7-3 reveals that all three alternatives retain their rank throughout and are very stable. The ER margin between the alternatives remains approximately constant as the major criteria weights are varied.

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 52 sensitivity runs were made for the analysis. These runs showed that preference rankings for certain sensors remained constant while others shifted within certain bands. Tables VII-XV through VII-XX show the resultant final scores and rank order of the alternatives as the indicated major criteria factor weights were varied for the four analysis techniques. The relationship among the evaluation scores for each alternative, the nominal weighting factors for the subcriteria and for the major criteria is as shown in Table VII-XI. Table VII-X additionally includes the maximum and minimum values for the major criteria. When the results were compared with the results obtained for RMS, Multiplicative and Logarithmic Weighting Techniques Alternative A always ranks first, C always ranks second, and B always ranks third. A high degree of stability in ER value exists between the alternatives for each of the criteria weighting factors and calculation techniques. For the Logarithmic Technique, the ER margin between the alternatives is decreased, especially between C and A, but otherwise, the results remain as previously reported. Therefore, the final ranking is:

RANK	ALTERNATIVE
1	All Single Channel Repeaters (A)
2	All Dual Channel Repeaters (B)
3	Both Dual and Single Channel Repeaters (C)

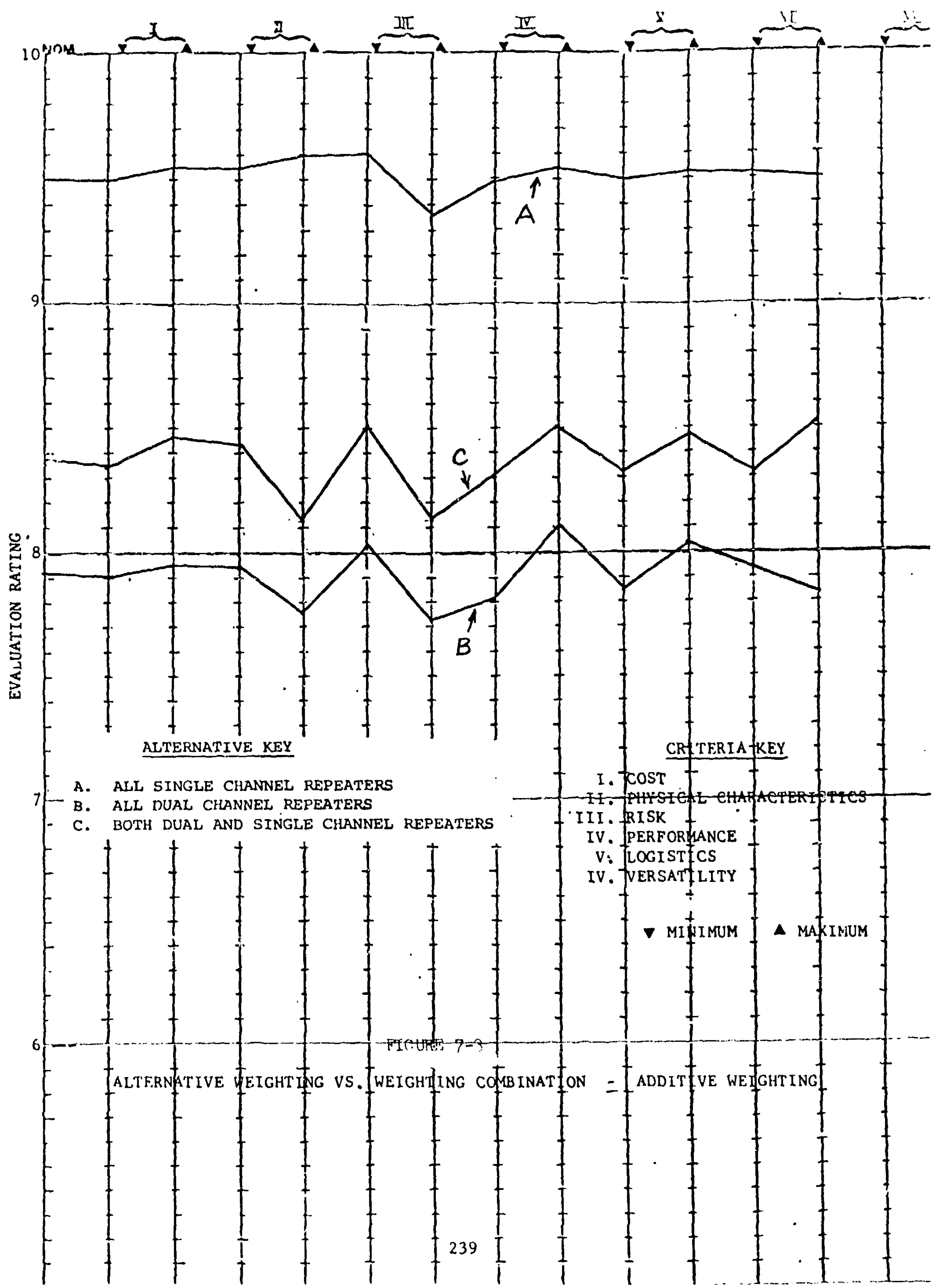


FIGURE 7-9

ALTERNATIVE WEIGHTING VS. WEIGHTING COMBINATION - ADDITIVE WEIGHTING

TABLE VII-XV

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING COST FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN COST								
A	9.49	1	9.52	1	9.46	1	9.64	1
B	7.90	3	8.04	3	7.77	3	8.63	3
C	8.34	2	8.53	2	8.13	2	9.16	2
MAX COST								
A	9.55	1	9.58	1	9.53	1	9.68	1
B	7.95	3	8.05	3	7.84	3	8.52	3
C	8.47	2	8.68	2	8.23	2	9.30	2

WEIGHTS USED IN THESE RUNS

MIN COST: COST = .2000; PHYS = .1778; RISK = .1778; PERF = .2133; LOG = .1245; VERS = .1067;

MAX COST: COST = .4167; PHYS = .1296; RISK = .1296; PERF = .1555; LOG = .0908; VERS = .0778;

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

TABLE VII-XVI

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING PHYSICAL CHARACTERISTICS FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PHYS								
A	9.49	1	9.51	1	9.46	1	9.63	1
B	7.95	3	8.05	3	7.82	3	8.64	3
C	8.43	2	8.62	2	8.20	2	9.24	2
MAX PHYS								
A	9.59	1	9.42	1	9.57	1	9.72	1
B	7.75	3	7.86	3	7.64	3	8.42	3
C	8.12	2	8.31	2	7.93	2	8.98	2

WEIGHTS USED IN THESE RUNS

MIN PHYS: COST = .2600, PHYS = .1333, RISK = .1734, PERF = .2080,
LOG = .1214, VERS = .1040,

MAX PHYS: COST = .2050, PHYS = .3167, RISK = .1367, PERF = .1640,
LOG = .0957, VERS = .0820,

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

TABLE VII-XVII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING DEVELOPMENT RISK FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	PMS RATING	PMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN RISK								
A	9.60	1	9.62	1	9.57	1	9.71	1
B	8.03	3	8.15	3	7.91	3	8.68	3
C	8.51	2	8.70	2	8.31	2	9.27	2
MAX RISK								
A	9.35	1	9.36	1	9.32	1	9.55	1
B	7.72	3	7.86	3	7.59	3	8.48	3
C	8.13	2	8.35	2	7.91	2	9.06	2

WEIGHTS USED IN THESE RUNS

MIN RISK: COST = .2650, PHYS = .1767, RISK = .1167, PERF = .2120,
LOG = .1237, VERS = .1060,

MAX RISK: COST = .2250, PHYS = .1500, RISK = .2500, PERF = .1800,
LOG = .1050, VERS = .0900,

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

TABLE VII-XVIII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING LOGISTICS FACTOR

ALTERNATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN LOG								
A	9.49	1	9.52	1	9.46	1	9.64	1
B	7.85	3	7.97	3	7.72	3	8.54	3
C	8.32	2	8.52	2	8.10	2	9.17	2
MAX LOG								
A	9.53	1	9.56	1	9.51	1	9.67	1
B	8.04	3	8.17	3	7.91	3	8.73	3
C	8.47	2	8.65	2	8.26	2	9.24	2

WEIGHTS USED IN THESE RUNS

MIN LOG : COST = .2595, PHYS = .1730, RISK = .1730, PERF = .2076, LOG = .0833, VERS = .1038,

MAX LOG : COST = .2312, PHYS = .1541, RISK = .1541, PERF = .1849, LOG = .1833, VERS = .0925, .

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

TABLE VI-XIX

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING PERFORMANCE FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PERF								
A	9.48	1	9.51	1	9.45	1	9.63	1
B	7.81	3	7.93	3	7.69	3	8.49	3
C	8.31	2	8.51	2	8.09	2	9.17	2
MAX PERF								
A	9.55	1	9.57	1	9.52	1	9.68	1
B	8.11	3	8.25	3	7.97	3	8.81	3
C	8.49	2	8.68	2	8.29	2	9.26	2

WEIGHTS USED IN THESE RUNS

MIN PERF: COST = .2656; PHYS = .1771; RISK = .1771; PERF = .1500;
LOG = .1240; VERS = .1062;

MAX PERF: COST = .2187; PHYS = .1059; RISK = .1059; PERF = .3000;
LOG = .1021; VERS = .0875;

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

TABLE VII-XX

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING VERSATILITY FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN VERS								
A	9.51	1	9.53	1	9.48	1	9.65	1
B	7.94	3	8.07	3	7.82	3	8.64	3
C	8.31	2	8.51	2	8.09	2	9.16	2
MAX VERS								
A	9.50	1	9.53	1	9.48	1	9.64	1
B	7.83	3	7.95	3	7.71	3	8.51	3
C	8.52	2	8.71	2	8.31	2	9.29	2

WEIGHTS USED IN THESE RUNS

MIN VERS: COST = .2592, PHYS = .1729, RISK = .1729, PERF = .2074,
LOG = .1210, VERS = .0657,

MAX VERS: COST = .2269, PHYS = .1513, RISK = .1513, PERF = .1815,
LOG = .1059, VERS = .1833,

ALTERNATIVE KEY

A. ALL SINGLE CHANNEL REPEATERS
B. ALL DUAL CHANNEL REPEATERS
C. BOTH DUAL AND SINGLE CHANNEL REPEATERS

9.0 CONCLUSIONS

Of the three alternatives considered, single channel repeaters received the highest ranking in all four weighting techniques used in the analysis. The alternative of providing both single and dual channel repeaters for REMBASS use ranked second in all weighting techniques, with the combined single/dual channel repeater design always last.

In reviewing the relative weights which were assigned to the various criteria, it was the conclusion of the team members that some of the weight assignments of the subcriteria were not realistic. For example, the subcriteria of cost which were improperly weighted were: a) acquisition costs; and b) life cycle support costs. Since the sensitivity analysis only considered the results of a perturbation of the major criteria (e.g., cost), these anomalies would not necessarily reverse the rankings of the alternatives, however, it would not reduce the difference between the first and second ranked alternatives. Whether the approximate 10% differential is significant for choosing an alternative has not been determined.

10.0 RECOMMENDATIONS

It is recommended that single channel repeaters be developed for REMBASS. In view of the factors discussed above, it is possible that dual channel repeaters may be cost effective in some applications. Therefore, it is also recommended tht development of dual channel repeaters as well as single channel repeaters be considered.

SECTION VIII

ENGINEERING ANALYSIS 7 - MODULATION TECHNIQUES

1.0 SUMMARY

This analysis addresses the modulation method to be used in the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated against a specific set of criteria; error performance, Rayleigh fading, Electronic Countermeasures (ECM) and Radio Frequency Interference (RFI), spectrum utilization and development risk. The DTS team recommended that the Binary Frequency Shift Keying (BFSK) alternative should be used in REMBASS. This recommendation was based on the analysis and operational considerations.

2.0 INTRODUCTION

This engineering analysis is a companion to engineering analysis 1. In that analysis various alternatives were explored from which a transmission technique (e.g., narrowband or wideband) may be selected. In this engineering analysis several common modulation methods will be compared on the basis of common criteria, which will be compatible with either transmission technique from engineering analysis 1.

3.0 STATEMENT OF THE PROBLEM

The objective of the REMBASS DTS is to provide a data link between sensors and readout terminals, either directly or via one or more repeaters. It is desirable that the link will be able to provide the reliability, error performance, interference immunity, etc., with the least cost, minimum power requirements, etc., with state-of-the-art technology. The method of modulation is a factor which influences the performance of the data link and therefore must be judiciously selected.

4.0 ALTERNATIVES

The alternatives to be evaluated as possible methods of modulation may be used in conjunction with either transmission technique of engineering analysis 1 and are therefore evaluated independent of a transmission technique.

a) <u>On-Off-Keying (OOK)</u> is a modulation method in which the carrier frequency is transmitted (transmitter <u>on</u>) for a fixed time interval to represent one source symbol and the transmitter is <u>off</u> for a fixed (similar) time interval to represent a complimentary or second source symbol.

b) Binary Frequency Modulation (BFM) is a modulation method in which the carrier is frequency modulated by a signal which is proportional to the data rate. The modulation index is adjusted to provide the bandwidth, error rate, etc., required at the receiver. The receiver utilizes a limiter/discriminator detector followed by a low-pass filter.

c) Binary Frequency Shift Keying (BFSK) is a modulation method in which the frequency of the carrier is shifted to one of two values. One carrier frequency is usually defined as the 'MARK' frequency, and the other carrier frequency is defined as the 'SPACE' frequency.

d) M-Ary FSK is a modulation method similar to BFSK except that there are now 'M' carrier frequencies, each of which has a one-to-one correspondence with a source symbol or a coded source symbol.

e) Phase Shift Keying (PSK) is similar to FSK except that the phase of the carrier frequency is shifted in discrete amounts in response to the modulating signals instead of the frequency. Binary PSK is a method whereby one source symbol signal may be represented by 'zero' phase shift of the carrier and a second symbol is represented by a phase shift of 180°. An absolute phase reference is required to decode the modulated signal.

f) Differential PSK differs from PSK in that the modulating symbol shifts the carrier phase a specified amount relative to the phase produced by the previous modulating symbol.

g) Chirp is a modulation method in which the carrier frequency is linearly increased or decreased in accordance with the modulating symbol. An increasing frequency is associated with one symbol, and a decreasing frequency is associated with a second symbol. The upper and lower limiting frequencies are usually the same for either symbol.

h) Linear FM is a modulation method in which the instantaneous frequency of the carrier is directly proportional to some characteristic of the modulating signal (e.g., the signal amplitude).

4.1 Definition of symbols used in this engineering analysis are given in Figure 8-1.

FIGURE 8-1

DEFINITION OF SYMBOLS

BFM	Binary FM
BFSK	Binary Frequency Shift Keying
B_I	Transmission Bandwidth
B_R	Data Rate Bandwidth
B_r	Relative Bandwidth = (Bandwidth/bit rate)
β	FM Modulation Index = $\frac{\text{frequency deviation}}{\text{modulating frequency}}$
D	Dispersion Factor = Chirp (Time-Bandwidth) Product
DPSK	Differential Phase Shift Keying
ΔF	Frequency Uncertainty
$\Delta(\ )$	Represents Differential of ( )
Δ	Spread Spectrum (Chirp) Bandwidth
E	Energy (Watt-sec) per Symbol or Bit
ECM	Electronic Countermeasures
f_c	Carrier Frequency, Hertz
f_d	Frequency Deviation from the carrier
k	Number of Information Bit Represented by a Coded Symbol M
L	Number of Binary Digits in a Message
LOS	Line-of-Sight
M	Number of Symbols Transmitted = 2^k
M-ary FSK	Multi-ary Frequency Shift Keying
N	Total Noise Power = η_o x (Noise Bandwidth)
η_o	Gausian Noise Density (Watts/Hz)
OOK	On-Off Keying
P_e	Error Probability
P_{eb}	Bit Error Probability
P_{es}	Symbol Error Probability
PSK	Phase Shift Keying
RFI	Radio Frequency Interference
SWD	Surface Wave Device (Acoustic Delay Line or Filter)
(S/N)	Signal-to-Noise Ratio
T_m	Duration in sec. of a Transmitted Symbol, M
γ	Symbol Used for (S/N)
γ_o	(S/N) Averaged over a Rayleigh Fading Cycle

5.0 CRITERIA

The criteria which will be used in the comparative evaluation of the alternatives associated with this engineering analysis are defined below. In paragraph 6.0 each of the alternatives will be analyzed on the basis of these criteria and where possible, parameters will be determined for each criterion. In performing the final evaluation, each criterion will be weighted in proportion to its importance as determined from the REMBASS Material Need (MN), or other sources.

5.1 Error Performance. This is a probabilistic criterion which relates the probability of a data bit, or message error at the receiver in terms of signal-to-noise ratio (S/N) for the particular modulation method.

5.2 Rayleigh Fading. This is a condition which arises in communication in which the signal level at the receiver may drop several dB in a very short period of time due to the signal being reflected from local moving objects and arriving at the receiver out of phase with signal arriving directly from the source. Within reasonably small percentage bandwidths, the fading is not frequency sensitive. To keep the average error rate within bounds requires significant additional (S/N) margins vs. a non-fading environment.

5.3 ECM & RFI. ECM & RFI are two causes of performance degradation in radio communication. Adequate signal levels at the receiver must be provided to overcome expected interference from these sources, and the required signal level is related to the modulation method among other things.

5.4 Spectrum Utilization. The efficiency with which the assigned radio frequency band is utilized is a criterion of significant importance. Some modulation methods require more bandwidth than others for a given data rate and therefore spectrum utilization may depend on the method.

5.5 Development Risk. This criterion is defined as the probability that a given alternative can be successfully developed to a production posture.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 General. With two exceptions all modulation methods to be considered herein are assumed to be used for binary signaling only. The terms MARK and SPACE are generally used to represent the modulated signal (carrier) state corresponding to the binary '1' and '0' data signal representation. M-ary FSK will be considered as a special case of FSK when M represents the number of modulation levels and is greater than two. In this a one-to-one correspondence between the binary data symbols (1,0) and MARK and SPACE no longer exist due to the requirement for a coder in the modulation system. Linear FM will be considered only for analog modulation and therefore the evaluation criterion of error rate will not be applicable to this modulation method but the systems may rather be compared on a signal-to-noise (or signal-to-quantization noise) basis. The evaluation criteria and alternatives have already been defined in previous sections of this report.

6.2 Requirements and System Parameters. Only those system requirements and parameters are included which are necessary for a comparative evaluation of the alternative modulation methods, and it is not intended that these parameters are necessarily those which will subsequently be selected for the REMBASS. It is anticipated that a perturbation of these parameters will not significantly influence the results of the evaluation.

6.3 Detection Processes. The characteristics of the data transmission in REMBASS are such that coherent detection at the receivers is not possible with most modulation methods and can only be approximated with others. However, in the evaluation both coherent and non-coherent detection processes will be assumed valid when evaluating error performance in both a Gaussian noise and Rayleigh fading environment. It might be argued that consideration of fading is only academic in view of the short range (10-15 km), line-of-sight, links which will be used in most cases, however, the REMBASS MN does indicate a requirement for ranges of 60-100 km, and whether or not these are line-of-sight may also be a moot point. From a different viewpoint, it is still academic to consider the impact of Rayleigh fading on the required (S/N) to maintain a given bit error probability, since the increase over a non-fading (Gaussian noise only) environment is of such drastic proportions that other means of overcoming the problem (e.g., diversity techniques) would be considered as an alternative. Nevertheless, as a comparative evaluation of modulation methods the influence of Rayleigh fading will be included.

6.4 Alternatives. Each alternative modulation method will be evaluated in terms of the selected criteria and the results tabulated for final analysis comparison. In addition those alternatives which appear to be the most likely candidates for the REMBASS DTS will be evaluated against additional performance measures to provide a broader base from which a final modulation method may be selected. See paragraph 4.0 for a definition of the alternatives.

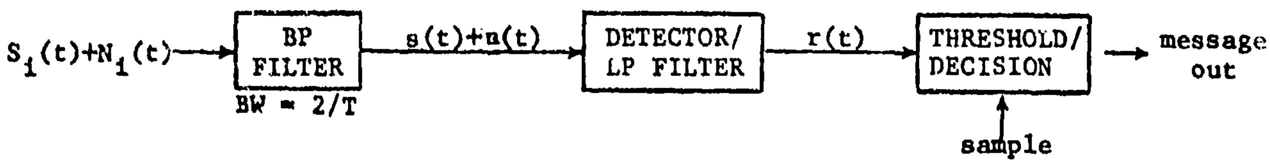
6.4.1 On-Off Keying (OOK). A binary OOK modulation is a form of amplitude modulation, sometimes called Amplitude Shift Keying (ASK), in which the carrier is transmitted to represent a MARK and the carrier is turned off to represent a SPACE. These pulses may be described by the following signals:

(1) $S_T(t) = A_T(t) \cos (W_c t + \phi_T)$

$$A_T(t) = \begin{cases} A_c; & \text{MARK} \\ 0\ ; & \text{SPACE} \end{cases} \qquad nT \leq t \leq (n+1)\ T$$

T = Symbol duration

These signals are received and processed after being corrupted by Gaussian noise, $n(t)$, of constant one-sided spectral density, n_0. Figure 8-2 is representative of a non-coherent processor and a corresponding coherent processor.



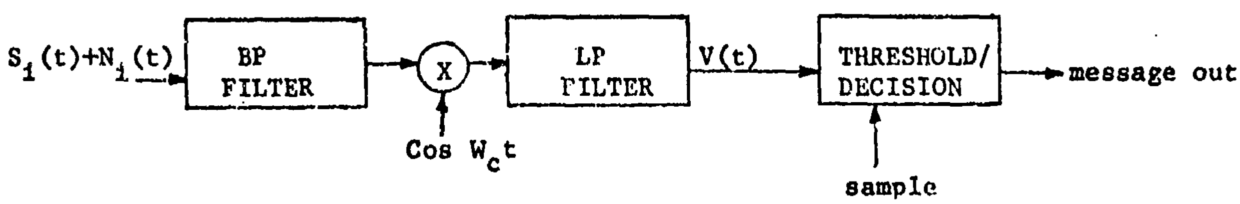
$$s(t) = A(t) \cos W_c t$$

$$r(t) = \sqrt{[A_T(t)+X(t)]^2 + Y^2(t)}$$

= Envelope of signal plus noise

$$n(t) = X(t) \cos W_c t - Y(t) \sin W_c t \quad \text{(narrowband noise)}$$

(a) Non-Coherent processor



$$V(t) = A_T(t) + X(t)$$

= Envelope of signal plus <u>in-phase</u> noise component

(b) Coherent processor

FIGURE 8-2

PROCESSING OF ON-OFF KEYING MODULATED SIGNALS

6.4.1.1 Error Performance

6.4.1.1.1 Gaussian Noise Environment. Error probabilities are determined on the assumption of equal probabilities of a MARK and SPACE being transmitted (during a message transmission). Errors will be made (bit error) where a SPACE is decoded as a MARK when the noise envelope exceeds the threshold setting, and also when a MARK is decoded as a SPACE due to negative noise envelope suppressing the signal envelope below threshold. The total probability of error is the sum of the two and is given by:1/

a) Non-Coherent Detection:

$$(2) \qquad P_e = \underbrace{1/2\ [1 - Q\ (\sqrt{2\gamma},\ b_0)]}_{\text{Prob. of MARK Error}} + \underbrace{1/2e - (b_0\ 2/2)}_{\text{Prob. of SPACE Error}}$$

$Q\ (\alpha,\beta)$ = Marcum Q-function

$\gamma = \dfrac{Ac^2}{2N}$ = (S/N) = pre-detection signal-to-noise ratio

b_0 = $B/\sqrt{N}$ = Threshold level normalized to RMS noise voltage in the bit-rate bandwidth

For increasing average (S/N), γ, and fixed threshold setting, b_0, the value of $Q \to 1$. Therefore, the minimum error probability is limited by the SPACE error probability, $1/2e - (b_0 2/2)$. For each γ and bit error rate there is an optimum value of b_0. This is one of the major disadvantages of OOK. A b_0 is increased, the threshold value of γ(that is, the value of γ below which the error rate increases precipitously), also is increased in an exponential manner at high γ's. In theory, optimum performance could be obtained by adjusting the threshold level, b_0, as a function of the (S/N). A more practical approach for slowly varying γ's is to use an AGC to reduce the noise power as the signal (carrier) level increases, thereby keeping the limiting error rate due to SPACE (noise) errors below the MARK error rate at a given γ. At large γ's and optimum threshold level, the bit error rate may be approximated by:

$$(3) \quad P_e \simeq 1/2e^{-\gamma/4}$$

This is still 3 dB worse than non-coherent FSK for the same P_e. Since the energy transmission during a SPACE (for OOK) is zero the energy during a MARK for OOK must be twice the energy for a MARK signal with FSK for the same bit error rate, and therefore, for the same data rate (bit period), twice the peak power per bit is required for OOK as compared to FSK.

1/ Modern Communication Principles, McGraw-Hill Book Co., S. Stein and J. Jones.

b) Coherent Detection:

$$P_e = 1/2 \left[1 - 1/2 \text{ erfc } \left(\frac{b_o}{\sqrt{2}} - \sqrt{\gamma}\right)\right] + 1/2 \left[1/2 \text{ erfc } \left(\frac{b_o}{\sqrt{2}}\right)\right] \quad (4)$$

erfc(χ) = complimentary error function
b_o and γ have the same meaning as before

It is clear that a similar threshold problem exists for coherent detection as for non-coherent detection. Since γ must be >> 1 to realize a reasonably low P_e, an approximation to 4 may be made at an optimum b_o. This is given by:

$$P_e \approx \frac{1}{\sqrt{\pi\gamma}} e^{-\gamma/4} \quad (5)$$

$b_o = \sqrt{\frac{\gamma}{2}}$ (optimum threshold)

A comparison of 5 and 3 would indicate that, under optimum conditions, coherent processing does not provide significantly better performance than non-coherent. This is also true of other methods if γ is sufficiently large, as will be seen.

6.4.1.1.2 Rayleigh Fading Environment. The error probability in a potential Rayleigh fading environment is given in terms of the (S/N), γ_o, averaged over a fading and non-fading environment. Since it is assumed that γ_o will be large, using 5:

$$\overline{P_e} \approx \frac{2}{\sqrt{(4 + \gamma_o)\gamma_o}} \approx \frac{2}{\gamma_o}; \quad \gamma_o >> 4 \quad (6)$$

From 6 it is evident that the performance in a fading environment is poor.

6.4.1.2 ECM & RFI. The OOK modulation being considered is narrowband and therefore has relatively good immunity to broadband noise-type ECM & RFI. The degree of susceptibility is proportional of the ratio of bandwidths of OOK signal and noise. Since the transmitted bandwidth is only a function of the data rate (neglecting carrier instability), this method of modulation involves no processing gain. The susceptibility to other types of countermeasures is equivalent to all narrowband, low data ratio modulation methods.

6.4.1.3 Spectrum Utilization. This performance criterion will only be considered in terms of the bandwidth utilized for a given data rate, since the number of channels available within a given system bandwidth will be proportioned to the required information bandwidth. The co-existence of other users within the same band will be dependent upon the message duration (among other things) and therefore is not necessarily related to modulation. Since the OOK method is essentially a pulse (constant amplitude) modulated carrier, the resultant frequency is $\left(\frac{\mathrm{Sin}X}{X}\right)$ related where:

$$X = (W - W_c)\,T/2 \qquad (7)$$

W_C = Carrier Frequency

T = Symbol duration

$= \frac{1}{\text{Symbol rate}}$

Therefore, the minimum transmission bandwidth is approximately:

$$B_I\ (\mathrm{OOK}) \approx 2/T \qquad (8)$$

6.4.1.4 Development Risk. Since OOK is one of the simplest and possibly oldest digital modulation methods the development risk is considered to be negligible. There are no required advanced development areas to advance the state-of-the-art prior to implementing this method.

6.4.2 Binary Frequency Modulation (BFM). After OOK this is perhaps the simplest method for modulation of a carrier with binary data. It differs from BFSK primarily in the manner or type of demodulation and detection used. In general the bandwidth of the baseband data is also restricted to the frequency nearest the fundamental. Demodulation and detection is performed by a limiter/discriminator followed by a low-pass filter. The signal is then sampled to convert the output back to a binary waveform which corresponds to the original binary sequence to within the required error rate. If the original binary sequence is converted to an NRZ binary waveform for modulation the minimum bandwidth of the modulating signal is DC up to the maximum sequence rate. If the binary sequence is converted to a Manchester coded (bi-phase) waveform, the bandwidth of the modulating waveform is restricted to Fs and 2 Fs where Fs is the binary sequence rate. This is essentially the DSPG Phase III sensor communication method. Since a limiter/discriminator may be used in either case, similar statistical analyses may be applied. The primary difference is that the error statistics will be somewhat influenced by the binary sequence in the NRZ method, whereas this is not necessarily true for bi-phase coding. A block diagram of a basic BFM receiver is shown in Figure 8-3.

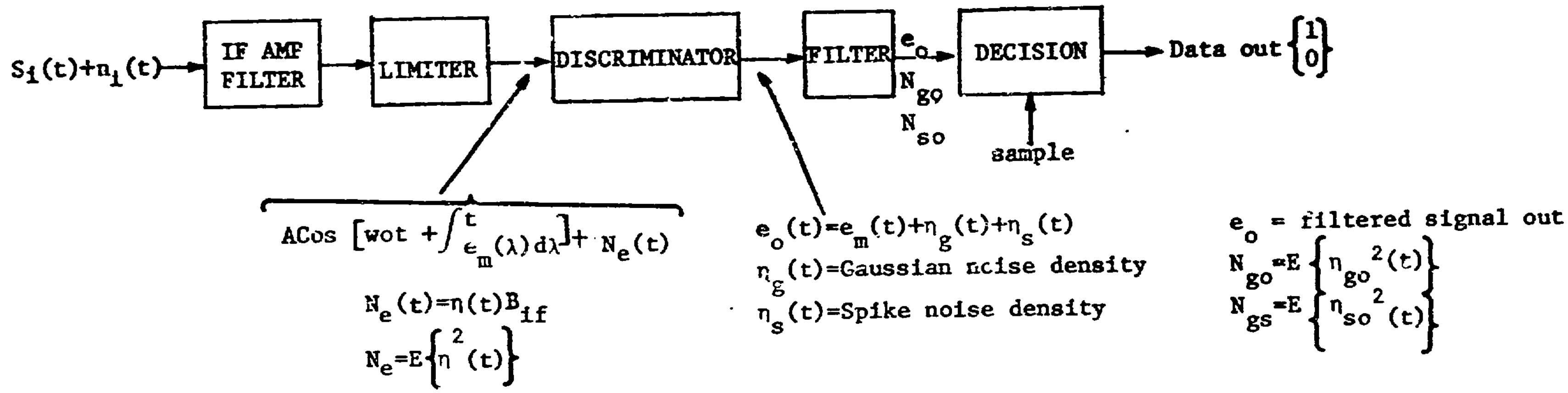


FIGURE 8-3

BINARY FM RECEIVER PROCESSOR

6.4.2.1 Error Performance. The performance of a limiter/discriminator processor, with a low-pass output filter, is well known when the modulating signal is analog and linearly frequency modulating the carrier. The validity of the analysis depends upon the carrier-to-noise ratio at the input being above a "threshold value". Predicting the performance of the BFM processor when the modulation is BFM or FSK has been somewhat less tractable due to the nonlinear nature of the demodulation process. Mazo,[2] and others have analyzed the performance in terms of error probabilities. The result of the analyses indicate that for narrowband systems ($\beta \leq 1$) the bit detection errors are a function of the Gaussian noise, or rather Signal-to-Gaussian noise density. For wideband systems, so-called "Click" errors predominate. The Mazo analysis applies to multilevel (>2) signals only. Schilling, et al,[3] have performed a similar analysis for binary signals. They also found that errors created by Gaussian type noise predominate at low β ($\beta < 1$), whereas for $\beta <$ 1 the errors are a result of spikes. Their results also indicated that the error probabilities depend upon the binary sequence if the modulating signal waveforms are NRZ. If Manchester coding of the binary sequence is used, this dependence should not exist. The error functions are given below for the indicated range of β.

a) $\underline{\beta < .734}$

(9) $$P_e \approx 1/2 \text{ erfc } \sqrt{\frac{\pi^2 \beta^2 \quad (\beta + 1)}{14.96 \; f_o \quad (\beta)} \left(\frac{A^2}{2N}\right)} \qquad \left(\begin{matrix}\text{Gaussian} \\ \text{noise region}\end{matrix}\right)$$

$$\text{erfc}[\chi] \approx \frac{\exp(-\chi^2)}{\sqrt{\pi}\,\chi} \; ; \; \chi > 4$$

$$\frac{A^2}{2N_1} = \gamma_{IF}$$

$$fo(\beta) \approx .75; \; \beta \approx .73$$

b) $\underline{.734 < \beta < 4.24}$

(10) $$P_e \quad (\beta,\gamma) \approx \frac{\beta}{\pi_2} \text{ Sin } \left(\frac{\pi}{2} \; \frac{D}{T}\right) \exp\,(-\gamma_{IF}) \qquad \left(\text{Spike region}\right)$$

$$\gamma_{IF} = \frac{A^2}{2N_1}$$

D = Approximate duration of spike at filter output

$$\frac{D}{T} = 0.755 \left[\ln\left(\frac{3\sqrt{2}}{\beta}\right)\right]^{1/2} \; ; \; \beta \leq 4.24$$

2/ "Theory of Error Rates for Digital FM" BSTJ 1966; J.E. Mazo and J. Salz.

3/ "Error Rates for Digital Signals Demodulated by an FM Discriminator" D.L. Schilling, E. Hoffman, E. Nelson, IEEE Trans. on Comm Tech 1967.

As β increases, D/T decreases so that the maximum P_e due to spike noise occurs at a β of about 3. Experimental results confirm the validity of 9 and 10 except that the errors in the spike region are somewhat less than predicted by 10 for reasonably large (S/N).

6.4.2.2 Rayleigh Fading. The performance of BFM with discriminator detection in a Rayleigh fading environment has not been determined. From 9 (low β) it is noted that the error function is of the same f rm as coherent FSK or PSK and for a given (S/N) the error rate s between the two. However, in the spike region (.7<β<4.2) the error function is of the same form as non-coherent FSK or coherent differential PSK. Therefore, the average error performance with Rayleigh fading may be approximated by:

a) $\beta \leq .734$

$$\overline{P}_e \approx \frac{1}{2}\left[1 - \frac{1}{\sqrt{1+\gamma_o\alpha}}\right]$$

where

$$\gamma_o = \text{(S/N) averaged over fading}$$

$$\alpha = \frac{\pi^2\beta^2(\beta+1)}{14.96\ f_o(\beta)}$$

$$\approx .82 \quad ; \quad \beta = .734$$

b) $.734 < \beta < 4.24$

$$\overline{P}_e \approx \frac{K}{1+\gamma_o}$$

$$K = \frac{\beta}{\pi}\,\mathrm{Sin}\left(\frac{\pi}{2}\frac{D}{T}\right)$$

$$K \approx .83 \quad ; \quad \beta = 3.14$$

γ_o = (S/N) averaged over fading

It should be emphasized that the error probabilities specified here (as with all the modulation methods considered) assumes that the pulse amplitude is statistically varying from pulse to pulse in a Rayleigh manner. Therefore, the significance of these error probabilities depends upon the data rate. For a data rate which is high compared to the fading rate, a better error statistic may be determined by averaging (weighting) the non-fading error rate over the (S/N) with and without fading rather than the probability density function of (S/N) with fading.

6.4.2.3 ECM & RFI. The performance of BFM in RFI would be good, as is most narrowband systems. It should also be good against broadband ECM but would be poor against other ECM.

6.4.2.4 Spectrum Utilization. Since the performance of BFM is optimized for β near 1 the bandwidth requirements will be directly proportional to data rate and carrier instabilities. That is, using Carson's rule, the bandwidth per channel is:

$$B_C = 2B_R(\beta+1) + 2/\Delta F/ \tag{11}$$

$$= 4B_R + 2/\Delta F/ \quad ; \ (B = 1)$$

B_R = Data rate bandwidth

$/\Delta F/$ = frequency instability in Hertz

6.4.2.5 Development Risk. There is no development risk involved with this method since all techniques are proven. Only if an improvement over the straightforward discriminator-filter detector is desired in the spike, (or Click) region would possible development be required. Some improvement could be achieved but the resultant complexity appears to exceed the factor of three improvements in bit error rate.

6.4.3 Binary FSK. This modulation method is similar to the BFM at the transmitter but is significantly different at the receiver processor. At the transmitter, it differs from BFM in that a shaping of the binary modulating waveforms is usually attempted in order to minimize the spreading of the modulated spectrum. In its simplest form two frequencies are transmitted at constant amplitudes (power). These may be represented by:

$$S(t) = \begin{cases} A \cos 2\pi(f_c+f_d)t; & \text{MARK} \\ & \qquad nT<t<(n+1)T \\ A \cos 2\pi(f_c-f_d)t; & \text{SPACE} \end{cases}$$

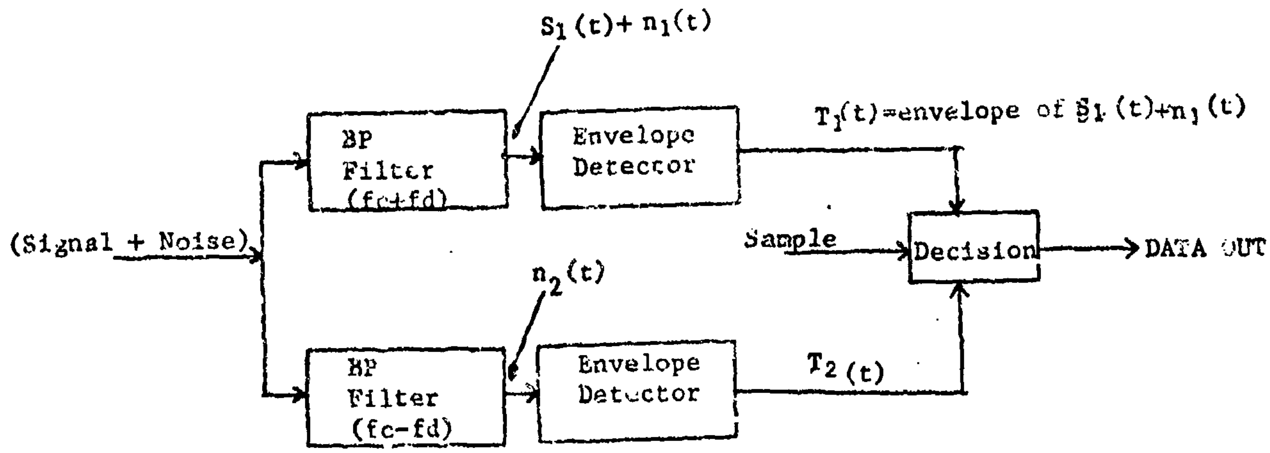
T = Period of each transmission

f_c = Median (carrier) frequency

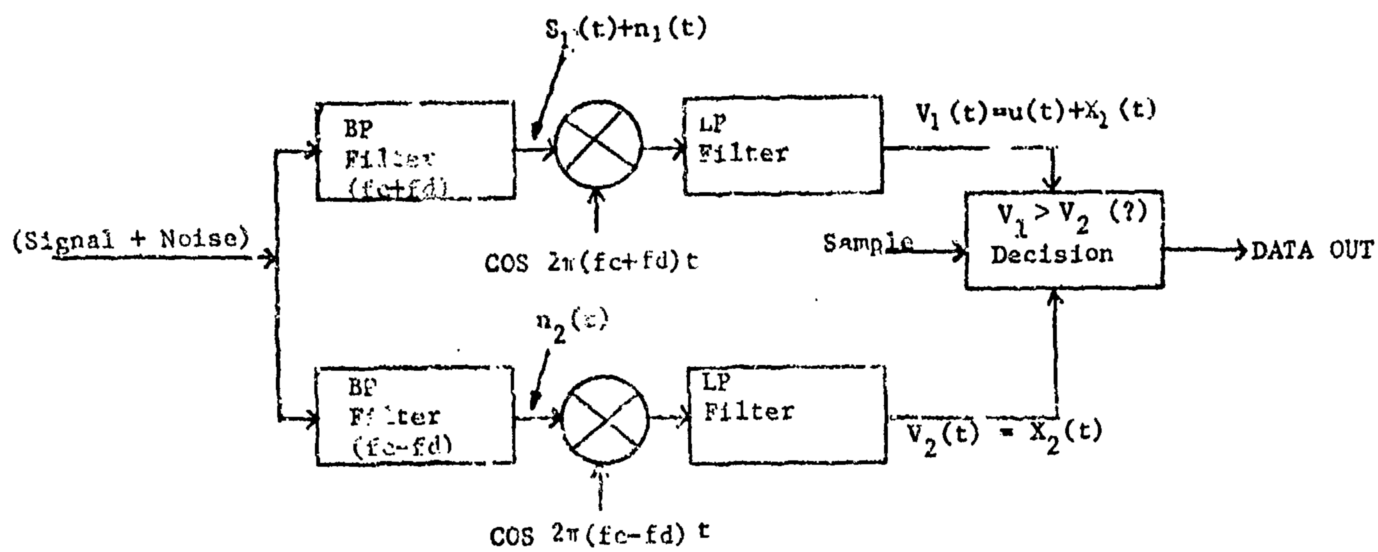
f_d = Deviation frequency

$A^2/2$ = Power (into unit load) of transmitted signal

The assumption is made that the rate at which the carrier is switched between MARK and SPACE is so related to the frequency deviation, f_d, such that the resultant spectra of the two signals do not overlap, except for possible overlap of the 'tails' of the spectra which are at a level considerably below that at the MARK or SPACE frequency. This will permit dual filter reception in the receiver such that the characteristic spectra of the filters do not overlap to any significant degree. The net result of these assumptions is no "crosstalk" and no noise correlation between filters. A block diagram of a coherent and non-coherent receiver processor is shown in Figure 8-4.



a. Non-Coherent BFSK Processor



b. Coherent BFSK Processor

FIGURE 8-4

BINARY FREQUENCY SHIFT KEYING (BFSK) RECEIVER PROCESSORS

6.4.3.1 Error Performance.

6.4.3.1.1 Gaussian Noise Environment. Error probabilities are determined on the assumption of equal probabilities of transmission of MARK and SPACE, assuming a one-to-one correspondence between the binary data sequence and the binary waveform transmitted. Also the previously stated assumptions regarding uncorrelated noise, etc., must apply.

a) Non-Coherent Detection:

(12) $$P_e/NC = 1/2 \exp - [\gamma/2]$$

γ = pre-detection (S/N) of the BP filter output containing the signal.

b) Coherent Detection:

(13) $$P_e/_c = 1/2 \operatorname{erfc}\left[\sqrt{\frac{\gamma}{2}}\right]$$

For reasonably large (S/N) an asymptotic expansion of erfc gives an error relation which may be easily compared to the non-coherent detection error probability, that is:

(14) $$P_e/_c \simeq \frac{1}{\sqrt{2\pi\gamma}} \exp - [\gamma/2]$$

Comparing (12) and (14), the difference between coherent and non-coherent detection is given by:

(15) $$P_e/_c - P_e/NC = \frac{1}{\sqrt{2\pi\gamma}} \exp - [\gamma/2] - \frac{1}{2} \exp - [\gamma/2] \simeq \frac{1}{2} \exp - [\gamma/2] = P_e/NC$$

Therefore, for high γ, the difference in error probabilities between coherent and non-coherent detection of BFSK is approximately equal to P_e/NC. In other words, the error probabilities are essentially equal for small error probabilities. This is the basis of the statement that non-coherent detection of BFSK is essentially optimum for large (S/N), or small error probabilities. However, if the ratios of error probabilities are considered, equation 16 results, which:

(16) $$\frac{P_e/NC}{P_c/c} \simeq \sqrt{\frac{\pi\gamma}{2}}$$

This indicates that (for a large γ) the error probability, at a particular γ, for non-coherent detection is significantly higher than for coherent detection. For a γ of 10 dB there is an order of magnitude difference. The error probabilities given above for non-coherent detection are based on the assumption that the bandwidth of the MARK and SPACE filters are only wide enough to accommodate the baseband data without severe distortion, and also that the detector is linear. Due to instabilities of the carrier, the filter bandwidths will be larger than the baseband data bandwidth and the detector's are non-linear at low (S/N). Therefore the performance will not equal that given by 12 except at high (S/N).

6.4.3.2 Rayleigh Fading. The average error probabilities for non-coherent and coherent processing are given in 17 and 18 below under conditions of Rayleigh type signal fading. These results must be considered in light of the caveats mentioned previously about bit rates:

(17) $$\overline{Pe}/_{NC} = \frac{1}{2 + \gamma_o} \qquad \text{(NON-COHERENT)}$$

(18) $$\overline{Pe}/_{C} = \frac{1}{2} \left[1 - \frac{1}{\sqrt{1 + \frac{2}{\gamma_o}}} \right] \qquad \text{(COHERENT)}$$

where γ_o = (S/N) averaged over fading

6.4.3.3 ECM & RFI. Against broadband noise, a narrowband FSK system would have the advantages of any narrowband system. Similarly, against RFI the performance depends on the bandwidth of the RFI compared to the sensor channel and whether they are collocated. BFSK performance against other types of ECM may not be as good due to the ease with which messages may be intercepted.

6.4.3.4 Spectrum Utilization. The transmission bandwidth requirement for BFSK modulation may be approximated by Carson's rule as follows:

(19) $$B_I = 2 B_R (\beta + 1) + 2 |\Delta F|$$

B_R = data rate bandwidth

β = modulation index = $\frac{f_d}{f_m}$

f_d = carrier deviation

$|\Delta F|$ = frequency instability in Hertz

If the modulation index (β) is large, FM is usually taken to be the bit rate. Otherwise, the binary modulation waveform is shaped to keep the energy within the minimum bit rate-bandwidth (BT) which is acceptable to other requirements such as the near/far ratio of emitters from receivers.

6.4.3.5 Development Risk. There is no risk associated with the development of the BFSK system since it has been used perhaps more than any other.

6.4.4 M-Ary FSK. In contrast to binary communication where two symbols are used (e.g., MARK and SPACE), M-Ary signaling involves the transmission of M unique symbols or signals. The method considered here incorporates M frequencies, one for each symbol and is therefore called M-Ary FSK indicating a similarity of BFSK. At the transmission end of the communication channel, a coder accepts k information bits in time T_m and converts these into $2^k = M$ frequencies via a modulator. Each frequency or symbol M_i, is transmitted for T_m seconds. At the receiving end, a bank of M filters is used to receive each of the M transmitted frequencies. Since phase information, as well as exact frequency information, is not considered to be available, non-coherent reception is assumed.

6.4.4.1 Error Performance. For purposes of computing the error performance it will be assumed that the spacing of the M frequencies is such that no crosstalk between channels occurs and the noise and signal set are uncorrelated. The signal will be envelope detected. Therefore, when a signal is present, all channel outputs except one will contain noise only. If all outputs are compared to determine the output with the largest envelope during the sampling interval the probability of error is found to have an upper bound which is a function of the (S/N) in the channel (symbol frequency M_i) containing the signal, and the number of symbols, or detection channels M. This upper bound is given by:

(20) $$P_e \leq \frac{M-1}{2} e^{-\gamma/2}$$ (symbol error probability)

where M = number of symbols, or frequencies

γ = symbol signal-to-noise ratio

The exact expression for P_e in terms of M and k is rather unwieldy and it is best to find its value from curves which have been prepared by computer integration of the error function.

In order to make a comparison between the performance of M-ary non-coherent FSK and BFSK (or other methods) it is customary to assume a fixed information rate R, where:

$$R = k/T_M = \text{information rate in bits/sec}$$

(21) $$k = \log_2 M = \text{information bits per symbol}$$

$$T_m = \text{symbol duration in seconds}$$

The power required for a given rate (R) is then compared for various symbol alphabets (M) versus binary symbol transmission. It can be shown that the normalized (S/N) per bit ($\gamma_b = \gamma/k$) decreases with increasing M for a given P_e (See Figure 8-5). This decrease in power requirement for a given information rate (R) is achieved by an increase in bandwidth requirement. At the same time, there is a (M/2) - fold increase in the receiver processing circuitry over a binary system since a separate filter and detection channel is required for each symbol (M) plus a sizeable increase in decision circuitry required for determining the greatest-of-M outputs. Finally, the equivalent average probability of information bit is related to the symbol error probability by assuming that when a symbol error is made, any of the other (M-1) symbols are equally likely to be selected instead of the correct one. This will be the case with M-ary FSK although it would not be true with some other modulation methods. In this case:

(22) $$P_{eb} = 1/2 \left[\frac{P_e}{\left(1 - \frac{1}{M}\right)}\right]$$

P_{e_b} = average information bit error probability

P_e = average symbol error probability

$M = 2^k$ symbols or signals

Therefore:

(23) $$\frac{P_e}{2} < P_{eb} \leq P_e \; ; \; (M = 2, 4, 8, \cdots)$$

6.4.4.2 Rayleigh Fading. Using the upper bound on the error probability given by 20, the error probability of an M-ary FSK with Rayleigh fading is similar to that for BFSK except for a factor (M-1) and the interpretation of (S/N). That is:

That is:

(24) $$P_e/RF \leq \frac{M-1}{2 + \gamma_o}$$

when γ_o = Symbol (S/N) averaged over fading.

6.4.4.3 ECM & RFI. The performance of M-ary FSK in an ECM or RFI environment will be dependent upon the value of M and therefore the number of bits per message. With a L-bit message there are 2^L unique messages. For large L it is obvious that M will be quite large if a unique frequency is associated with each message. The M-ary modulation method takes on the character of a frequency hopping transmission system and its susceptibility to ECM & RFI would be comparable. Since the probability of a given message occurance must be assumed random the receiver cannot be synchronized with the transmitter in order to reduce receiver complexity. This precludes the use of large values of M in a practical REMBASS system. Large message length must be broken up into k-bit segments such that a given message is transmitted as a sequence of (L/k) symbols, or frequencies, which are spread across a frequency band M/T_m, where T_m is the duration of a symbol. It is therefore possible that the susceptibility to spot detection would be less than if the message was transmitted BFSK at the same information (bit) rate. Against broadband noise or localized RFI, improved performance would be possible, since the power required for a given bit error probability decreases with M. Therefore for the same power output a margin is obtained against Gaussian type noise with increasing M. For M=8, (k=3), a margin of about 4 dB is possible as compared to BFSK. The margin does not increase directly with M.

6.4.4.4 Spectrum Utilization. The improved performance of M-ary FSK over binary FSK modulation is obtained at the expense of additional bandwidth requirements. The relative bandwidth increases as the number of bits per symbol (where the information rate is constant) as:

$$B_r = \frac{2M}{k} = \frac{2^{(k+1)}}{k} \qquad (25)$$

k = information bits per symbol M

B_r = Relative bandwidth (Bandwidth/bit rate)

Figure 8-5 is a plot of the bandwidth and (S/N) per bit, at a P_e of 10^{-5}, as a function of k (or M). It can be seen that the bandwidth requirement increases at a faster rate as k increases. The required γ_b decreases as k increases but the rate of decrease becomes less with increasing k. Consequently the trade-off between bandwidth and γ_b becomes less attractive for a k value above 3 or 4. The optimum value of k is 2 since no increase in bandwidth is required to transmit two bits per symbol vs one bit per symbol and the power required is almost 50% less for the same symbol error rate of 10^{-5}. This reduced power requirement is accomplished at the expense of a coder and four-frequency modulator in the transmitter as well as double the amount of filters and detectors in the receivers. If bandwidth is at a premium, rather than power, the same bandwidth may be used to accommodate twice the information bit rate for M=2 (BFSK) at the expense of the 2.4 dB increase in power, the bit error rate remaining constant at 10^{-5}.

6.4.4.5 Development Risk. There is no appreciable development risk associated with M-ary FSK systems if the value of M is not large. M-ary systems are not new and development activities would be directed toward approaching the maximum performance predicted by analysis.

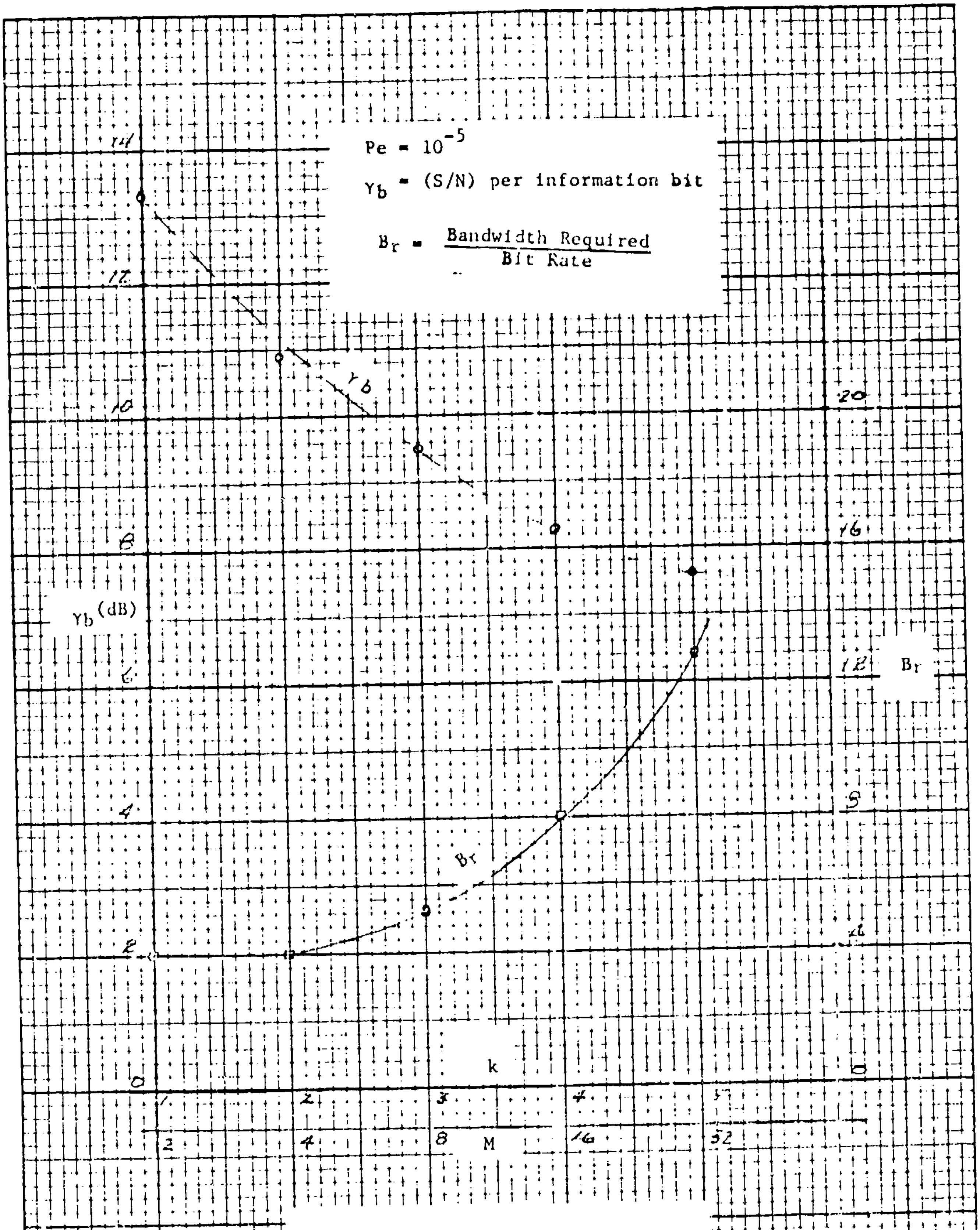


FIGURE 8-5

BANDWIDTH + (S/N) REQUIREMENTS VS k

6.4.5 Phase Shift Keying (PSK). Whereas BFSK and M-ary FSK are digital forms of FM, PSK may be considered the digital form of PM. Although PSK can be shown to be the optimum binary modulation method in terms of minimum bit error probability for a given bit energy, it has limited applications in practice due to the requirement for a coherent detector in the receiver for recovering the digital data. Matched filters are available for performing the modulation and demodulation process although the processing gain achievable at present is limited. Nevertheless, in certain applications, PSK modulation, using surface wave devices (SWD's) as matched filters, is a viable communication method. For the binary PSK modulation method the optimum choice of signals to represent the binary digits of 0 and 1 is that which makes:

$$S_0\ (t) = -S_1(t)$$

where

S_0 (t) = signal representing a binary '0'

S_1 (t) = signal representing a binary '1'

Also the transmitted signals are arranged to contain the same energy, or equal power, since their duration (T) is generally the same. A matched filter (or correlator) at the receiver followed by sampling at intervals of T will produce the maximum (S/N) for the given signal energy and white noise at the filter input. Due to the difficulty of providing a reference signal in the receiver with correct frequency and phase, the correlator (coherent) processor is not a practical implementation for burst type data messages of the REMBASS type. However, acoustic delay lines may be fabricated to provide a matched filter operation and this technique is used with PSK modulation to provide good performance with certain wideband transmission systems, such as pseudo-noise coded spread spectrum. Typical signal waveforms which fulfill the above relation between S_1 and S_2 are:

$$S_1\ (t) = A \cos W_c t$$

$$S_2\ (t) = A \cos (W_c t + \pi)$$

When W_c is either the carrier frequency or an intermediate frequency depending on the structure of the modulator.

6.4.5.1 Error Performance. As indicated previously, a coherent PSK digital modulation system provides the lowest bit error probability of all. It is related to the bit energy in a white Gaussian noise environment by:

(26) $$P_e = \frac{1}{2}\,\text{erfc}\,\sqrt{\frac{E(1-\lambda)}{2\,\eta_o}}$$

where

erfc(x) = Complimentary error function of (x)
E = Average signal energy/bit

η_o = One-sided noise spectral density

λ = Cross correlation coeff. of the binary modulation waveforms over their equal time interval T.

For the optimum system, the binary signals are correlated an $\lambda = -1$. In this case the error rate is minimized and is given by:

(27) $$P_e = \frac{1}{2}\;\text{erfc}\;\sqrt{E/\eta_o} = 1/2\;\text{erfc}\sqrt{\gamma}$$

6.4.5.2 Rayleigh Fading. The error performance of a coherent PSK modulation system in a Rayleigh fading environment is given by:

(28) $$\overline{P_e} = \frac{1}{2}\left[1 - \frac{1}{\sqrt{1 + \left(\frac{1}{\gamma o}\right)}}\right]$$

where

γ_o = mean (S/N) averaged over fading and non-fading as before. Whereas in a non-fading environment, the error performance of coherent PSK is significantly better than other modulation methods, the relative difference is not great where reasonably low average error rates are required in a slow, non-selective, Rayleigh fading environment. For large γo · 28 becomes:

(29) $$P_e = \frac{1}{4\gamma o} \qquad ;\ (\gamma o >> 1)$$

For a given (S/N) the error probability of ideal PSK may be two or more orders of magnitude less than other methods. In a fading environment the difference is not too significant at high γo's.

6.4.5.3 ECM & RFI. In applications where coherent PSK may be used with matched filters (SWD's) (such as spread spectrum systems), a small amount of processing gain, and therefore some interference margin, may be obtained. To obtain significant margins requires special techniques such as transmiting a reference signal forthe receiver to use in establishing and maintaining frequency and phase coherence by a special tracking loop (PLL).

This requires additional power which does not contribute to the (S/N) of the transmitted data. Unfortunately, in order to maintain coherence a high (S/N) is required in the tracking loop. Viterbi[4/] has shown that the optimum detector for "partially" coherent reception is a linear combination of the non-coherent detector and the purely coherent detector, where the relative weighting coefficients are 1 and 2 α respectively. The parameter α is the effective (S/N) in the tracking loop. Whether the added complexity of the receiver is worth the additional performance improvement during periods of large α (>10 dB) would obviously depend upon the application. However, unless the signal waveforms are correlated (or almost so) the dual processing required is of questionable value. A typical coherent PSK receiver is shown in Figure 8-6.

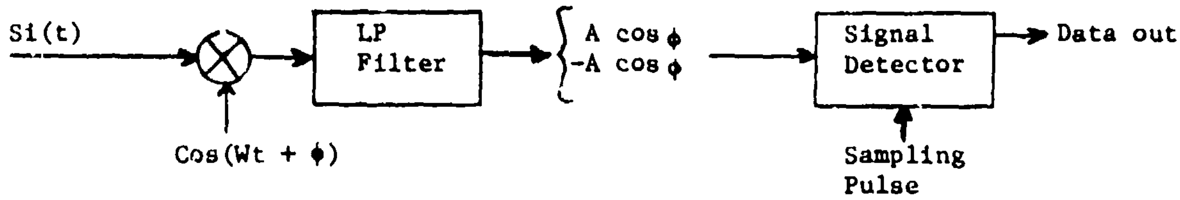


FIGURE 8-6

COHERENT PHASE SHIFT KEYING

6.4.5.4 Spectrum Utilization. The relative bandwidth, B_r, (bandwidth per data bit rate) for a coherent PSK system is given by:

(30) $$B_r = \frac{C}{\log_2 M} = \frac{C}{k}$$

M = Symbol set (number of phases)

$= 2^k$

k = data bits per symbol

C = constant $\leq$ 2

4/ "Optimum Detection and Signal Selection for partially Coherent Binary Communication" Viterbi, A. J., IEEE Trans on Info Theory, April 1965

For a binary PSK system k = 1 and the relative bandwidth is about 1/2 the required bandwidth for a BFSK system which is not too significant at low data rates. Comparing 25 and 30, it is seen that (ideally) the relative bandwidth increases exponentially with k for M-ary FSK, whereas it decreases inversely with k for M-ary PSK. However, with M-ary FSK the energy per bit decreases with increasing M but the converse is true with M-ary PSK. Since availability of bandwidth is not considered as much of a constraint as power, the bandwidth efficiency of PSK would have limited utility for REMBASS as compared to other methods.

6.4.5.5 Development Risk. Although choerent phase modulated data communication systems have been built in which coherence between the receiver and transmitter signals is maintained with a PLL in the receiver, it cannot be said that there is no risk attached to the development of this type system for REMBASS. When the burst characteristic of the data signals are considered, as well as the fact that high (S/N) cannot be insured, it is doubtful that the predicted performance could be approached very closely in this manner. Phase shift modulation is a natural modulation method for analog matched filters such as SWD's. In this case, coherence is only a function of mechanical and temperature characteristics of the SWD's and can be controlled to within about 1 dB of theoretical performance. The major disadvantage with this technique is that there is a state-of-the-art limit at present on the minimum tolerable data rate of about 50×10^3 b/s. Therefore it is usually reserved for coded spread spectrum transmission systems. A more recent development using solid-state semi-conductor techniques has resulted in matched filter for low data rate applications. These techniques, called charge-transfer devices (CTD's), will provide a complimentary capability to the SWD's, and permit use of PSK modulation for low data rate narrowband transmission systems. Although these CTD's have not reached the state-of-the-art category of SWD's, it is expected that they will be available for general use in the near future. Nevertheless, a reasonable development risk should be associated with PSK.

6.4.6 Differential Phase Shift Keying (DPSK). This modulation technique is sometimes called a differential "coherent" phase shift keyed system, although the implementation of the method does not have all the attributes of a coherent system. The transmitted waveforms are the same as PSK in order to obtain a cross correlation of -1. The differential aspect of the method arises in that absolute phase is not essential. Decoding is performed by comparing the phase of each bit with the previous bit to determine if a change in phase has occurred and therefore identifying the code bit sent. In view of the fact that the "reference" signal is a transmitted signal also, and therefore corrupted by noise, errors are no longer independent. In fact errors tend to occur in pairs in a DPSK system. Whether or not this is important depends upon the application.

Where a set of symbols is transmitted as binary code groups, two consecutive errors would generally be no more significant than a single error. However, a single bit error correcting code would be of little use when errors are likely to occur in pairs.5/ A typical DPSK receiver is shown in Figure 8-7.

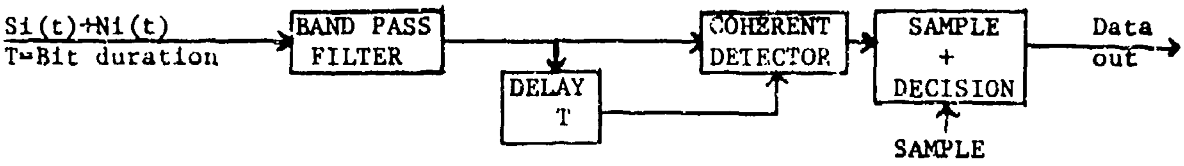


FIGURE 8-7

DIFFERENTIAL PHASE SHIFT KEYING RECEIVER

6.4.6.1 Error Performance. If the reference signal was not subject to the same noise as the signal being compared the probability of error for DPSK would be the same as coherent PSK. Due to the noise perturbations of the reference signal the DPSK error rate is given by:

(31) $$P_e = 1/2 \exp(-\gamma)$$

$$\gamma = \text{average } (S/N) = (E/\eta_o)$$

This is the asymptotic value approached by coherent PSK for large (E/η_o). Although, for a given error rate, the difference in required (E/η_o) between coherent PSK and DPSK approaches zero for small error rates, the difference in error rates for a given (E/η_o) increases with reduced error rates. That is, the ratio of error rates for DPSK and PSK diverges, just as does non-coherent and coherent FSK.

Comparing DPSK and non-coherent FSK it is seen that an increase of 3 dB (S/N) is required for FSK over DPSK at the same error rate.

6.4.6.2 Rayleigh Fading. In view of the similarity of error rate performance between FSK and DPSK it is not surprising that a similarity exists between their performance under non-selective, slow Rayleigh type fading conditions. For DPSK this is given by:

5/ "Comparison of Binary Data Transmission Systems" John G. Lawton, Cornell Aeronautical Laboratory, Inc.

(32) $$\overline{P_e}/_{RF} = \frac{1}{2+2\gamma_o}$$

γ_o = (S/N) averaged over a fading cycle

For large γ_o (>>1) the error rate for DPSK is only one half that for FSK at the same γ_o, and it is twice that for PSK. Therefore, under conditions of slow Rayleigh fading signals, selection of FSK, PSK or DPSK would be made on the basis of something other than average error performance. Of course during the intervals of no fading the relative error performance would be significantly different.

6.4.6.3 ECM & RFI. With comparable data rates, power, etc. the performance of DPSK against broadband noise or RFI would be a little better than FSK but not as good as PSK for reasons of bandwidth and error performance already mentioned. Against other types of interference, other factors might determine the relative performance of DPSK vs other methods.

6.4.6.4 Spectrum Utilization. Since the modulation procedure for DPSK is a discrete shift in phase for the transmission of data, similar to PSK, the bandwidth requirements for a given data rate should be the same as PSK. As compared to other methods, it would be equally good or better than most, depending on the data rate.

6.4.6.5 Development Risk. There should be no particular risk involved in implementing a DPSK system. Two methods are currently common, either of which would work satisfactorily at the expected REMBASS data rate requirements. Techniques utilizing integrate-and-dump (I&D) filters have limitations above several kilobits per second but it is not expected that REMBASS requirements will exceed this unless digitized analog data is transmitted.

6.4.7 Chirp. Pulse compression/decompression modulation techniques were developed at the Bell Telephone Laboratories in the early 1950s for applications in radar. The work was declassified and reported by Klauder, et al in 1960 6/. It was at Bell that the name "Chirp" was coined to describe the process of linear FM which Chirp uses. This principle has subsequently been applied to data modulation, but without the success which it provided in radar application. In its simplest form, a transmitter generates a constant amplitude RF pulse of duration T, during which time the frequency is changed, by an amount Δ, from some initial value f_1 to a final value f_2 at the end of time T. At the receiver the frequency modulated pulse is passed through an appropriate network (dispersive filters) and the pulse is "collapsed" from a pulse of duration T to one of duration $1/\Delta$, approximately. Since energy is conserved, the power gain is proportional to $T\Delta$. In radar this term is called the Dispersion Factor; in communications it is usually given the name Processing Gain (against White Gaussian noise).

6/ "The theory and Design of Chirp Radars," The BSTJ, Vol. 39, 1960 pp. 745-808, J. R. Klauder, A. C. Price, S. Durlington, and W. J. Albersheim.

In practice, two factors may limit the full utilization of this principle: 1) the design of networks (active or passive) to provide the complementary frequency dispersion characteristics desired; and 2) sidelobes on the collapsed pulse. The first problem has been alleviated by the recent application of SWD's as linear dispersive filters 7/. The second problem is of most concern for low TΔ products (<50). Until recently the sidelobes have been suppressed by applying weighting functions to the frequency response function of the linear FM filter. This had the deleterious effect of reducing the (S/N) and widening the output pulse from the theoretical value. For a large TΔ product (>100) the loss in (S/N) may be only a few decibels. The primary problem was the complexity of the frequency weighting operation. This problem has been simplified, again by the use of SWD's, in which non-linear FM pulse compression filters have been designed which considerably reduces the amplitude of the sidelobes, even at low TΔ products 8/.

In data communication the larger the TΔ product (Processing Gain) the better. However, the application of SWD's to Chirp modulation/demodulation systems have similar limitations as with coded spread spectrum applications. Since the pulse duration TΔ is limited large TΔ's can only be achieved by increasing the bandwidth of the Chirp signal. Bandwidths of up to 40% have been reported utilizing special design techniques 9/. Chirp, as a modulation method for data communication is essentially a form of spread spectrum and therefore, has similar attributes and disadvantages as a pseudo-noise coded spread spectrum system. However, there are applications in which the Chirp modulation technique are superior to PNSS 10/.

6.4.7.1 Error Performance. The error performance of a Chirp modulation DTS would be equally as good as other coherent systems, assuming that a matched filter Chirp system is approximated using "tailored" SWD's. Chirp may be applied in an OOK mode but would have the detection and processing limitations of OOK, with

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7/ "Ranging and Data Transmission Using Digital Encoded FM-Chirp Surface Acoustic Wave Filters." IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-21 No. 4, April 1973, J. Burnsweik and J. Wooldridge.

8/ "Implementation of Non-Linear FM Pulse Compression Filters Using Surface Wave Delay Lines," J.C. Worley, Sperry Rand Research Report, March 1971.

9/ "Highly Dispersive Acoustic Filter Study," Hughes Aircraft Interim Report, Contract No. DAAB07-71-C-0046.

10/ "Linear FM, Spread Spectrum Signal Formats for Beacon and Communication Systems," by C.E. Cook, MITRE WP-4212, 16 February 1972.

the exception of the resultant processing gain and noise immunity of Chirp. The more likely implementation would be similar to M-ary FSK. Within a given time or frequency space various $T_i\Delta_j$ products with both positive and negative slopes could be configured. A single receiver could process all signals within a specified maximum $T\Delta$ range. The particular $T_i\Delta_j$ assigned to a given sensor (field) would be a function of the distance from sensor to receiver, and therefore, the post-detection (S/N) at the receiver would be somewhat normalized for all sensor fields. This has the obvious disadvantage that the crosstalk between filters for complementary signals (1, or 0), as well as certain interference signals, is inversely proportional to the $T\Delta$ product and would therefore be different for different fields. The simplest implementation is a method whereby a positive Chirp (f vs. t) is used for one symbol (e.g., binary 1) and an equal negative Chirp is used for the second (complimentary) symbol. In this way the peak amplitude response of the filter matched to the 'one' (zero) Chirp due to the linear FM signal representing a 'zero' (one) is given by:

$$R = \frac{1}{\sqrt{|\delta| T\Delta}} = \frac{1}{\sqrt{2T\Delta}}$$

where

$$|\delta| = \left|\frac{S_1 - S_0}{S_0}\right| = 2$$

$$S_1 = \frac{\Delta_1}{T_1} = -\frac{\Delta_0}{T_0} = -S_0 \quad \text{(by design)}$$

Due to the 'smearing' of the energy over a longer time interval by the 'non-matched' filter, a consecutive sequence of like symbols (1's or 0's) would cause a linear build-up of the noise in the 'non-matched' filter output with a resultant degradation of output (S/N). The signals described above to represent the binary symbols 1 and 0 can be shown to be essentially orthogonal for large $T\Delta$.[11/] Therefore, the probability of error for a dual matched filter "Chirp" FM system would be similar to a matched filter FSK system, i.e.,

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11/ "Noise Immunity of a Digital Data Transmission System Using Linearly Frequency-Modulated Signals," Telecommunications, Vol. 22, No 4, 1964; D.L. Zaytdev and V.I. Zhuravlev.

$$P_e \geq 1/2 \text{ erfc } \frac{E}{2\eta_o} \quad ; \text{(Matched Filter)}$$

$$= 1/2 \text{ erfc } \sqrt{\gamma}$$

6.4.7.2 Rayleigh Fading. The performance of Chirp modulated data systems in a reflective-multipath fading environment is dependent upon the path delay between the signal paths in relation to the TΔ product of the Chirp signal. Since a Chirp matched filter processor can process overlapping input signals as long as the time difference between the compressed pulses is greater than $\frac{1}{\Delta}$ (ideally), 12/ the path difference for reflected signals must be greater than T/D, where T is the duration of the Chirp signal and D is the "dispersion factor" (6) of the matched filter. This is in contrast to other modulation methods, and particularly PN coded spread spectrum, in which any overlapping of input signals may cause interference depending on the relative phase of the direct and reflected signal at the receiver input. In this regard, Chirp would be superior to most frequency modulation methods.

6.4.7.3 ECM & RFI. The Chirp modulation method of binary data communication is a method of bandwidth spreading. Assuming a matched filter processor in the receiver, the processing gain is directly proportional to this bandwidth expansion factor as with other coherent systems. Against a power-limited noise jammer, the effective jammer noise power at the matched filter output is inversely proportional to the processing gain. Consequently, the Chirp performance is similar to other methods against this type of interference. Against a continuous CW signal within the filter bandwidth, the only effect of the matched filter is to delay the signal in proportion to the frequency but the output power of the CW signal is essentially unchanged through the filter. Therefore, the Chirp performance depends upon the relative power levels at the input to the matched filter, the processing gain and the required error performance. This is in contrast to other modulation methods where the CW frequency (or modulation) may correlate with the coherent processor to cause added interference at the processor output. Against impulse-type noise signals, the Chirp matched filter delays the frequency components of the impulse causing a "smearing" of the pulse energy and, therefore, produces an effective peak power reduction at the output. Since the sampling time of the filter output for the data signals is inversely related to the bandwidth expansion factor, the pulse energy-to-noise density is accentuated during the sampling interval and the impulse noise is suppressed. 13/

6.4.7.4 Spectrum Utilization. Overlapping Chirp signals can be resolved without serious interference if the signals have a time difference equal to or greater than ($1/2\Delta$) where Δ is the bandwidth of the linear Chirp signals, assumed to be equal. This is in contrast to coded spread spectrum signals where the probability of interference between overlapping signals may be strongly influenced by the relative phase of the two signals.

13/ "Swept Frequency Modulation", E.K. Holland-Moritz, J.C.Dute and D.R. Brundage, University of Michigan, Institute of Science and Technology.

12/ "Coming to Grips with Multipath Ghosts" Electronics, Nov. 27, 1967, D. S. Deyton

In this sense, Chirp has a potentially improved spectrum utilization. Being able to resolve overlapping Chirp signals requires increased complexity in the receiver, depending on the number of message overlap expected. In a REMBASS communication system which may utilize several repeaters in each link, the receiver should be as simple as possible. Therefore, the maximum utilization of the spectrum, which results in a complex receiver, may not be desirable. The system spectrum may be divided into several channels in order to accomodate more signals (sensors) but a reduction in AJ margin accompanies the resultant decrease in time-bandwidth product of the Chirp signal. All things considered, the spectrum utilization of Chirp modulation for REMBASS is not considered to be too satisfactory.

6.4.7.5 Development Risk. If time-bandwidth products of about 500 or less are assumed, the development of a Chirp communication system using acoustic delay lines is not considered to be a high risk. SWD's have been built with time-bandwidth products of 1,000 or greater but these are expensive and are not considered to be state-of-the-art.

6.4.8 Linear FM. Linear FM is a means of transmitting analog information by frequency modulating the carrier in proportion to the amplitude of the analog signal. Therefore, it is not considered as a means of transmitting digital data. When a choice of modulation for REMBASS digital data is selected an analysis will then be performed to determine the relative merits of using linear FM for the analog data versus digitizing the analog data and using the same modulation as for digital data.

TABLE VIII-I

SUMMARY OF ERROR PERFORMANCE ANALYSIS

ALTERNATIVE	PROBABILITY OF ERROR FUNCTIONS (BIT OR SYMBOL)		
	COHERENT	NON-COHERENT	WITH RAYLEIGH FADING
OOK	$P_e \approx \frac{1}{\sqrt{\pi\gamma}} \exp(-\gamma/4)$ $(\gamma >> 1)$	$P_e \simeq 1/2 \exp(-\gamma/4)$ $\left(\gamma >> 1;\ \text{optimum threshold}\right)$	$\overline{P}_e \approx \frac{2}{\gamma_0}$ $(\gamma_0 >> 4)$
BFM	$P_e \simeq 1/2\ \mathrm{erfc}\sqrt{\frac{\pi^2\beta^2(\beta+1)}{14.96\, f_d(\beta)}\gamma}$ $\gamma = (C/N)_{IF}$ Gaussian region; $\beta < .734$ (NOTE 1)	$P_e \simeq \beta/\pi\ \mathrm{Sin}\left(\frac{\pi D}{2T}\right)\exp(-\gamma)$ $\gamma = (C/N)_{IF}$ Spike region; $.734 < \beta < 4.74$ (NOTE 1)	$\overline{P} \simeq 1/2\left[1 - \frac{1}{\sqrt{1+\alpha\gamma_0}}\right]$ $\beta = .734,\ \alpha = .82$ $\overline{P}_e \simeq \frac{.77}{1+\gamma_0}$ $\beta > .734$
BFSK	$P_e = 1/2\ \mathrm{erfc}\sqrt{\gamma/2}$ $\simeq \frac{1}{\sqrt{2\pi\gamma}} \exp(-\gamma/2)$ $(\gamma >> 1)$	$P_e = 1/2 \exp(-\gamma/2)$	$\overline{P}_e = \frac{1}{2+\gamma_0} \simeq \frac{1}{\gamma_0}$ (non-coherent) $\overline{P}_e = \frac{1}{2}\left[1 - \sqrt{\frac{1}{1+\frac{2}{\gamma_0}}}\right]$ (coherent)
M-Ary FSK	(Not Applicable)	$P_{es} \leq \frac{M-1}{2} \exp(-\gamma/2)$ (symbol error) $P_{eb} = 1/2 \frac{P_{es}}{\left[1-\frac{1}{M}\right]}$ (Bit error)	$\overline{P}_{es} \leq \frac{M-1}{2+\gamma_0}$ $\overline{P}_{eb} = 1/2 \frac{P_{es}}{\left[1-\frac{1}{M}\right]}$
PSK	$P_e = 1/2\ \mathrm{erfc}\sqrt{\gamma}$ $\simeq \frac{1}{\sqrt{2\pi\gamma}} \exp(-\gamma)$ (correlated signals, $\lambda = -1$)	(Not Applicable)	$\overline{P}_e = \frac{1}{4\gamma_0}$ $(\gamma_0 >> 1)$

NOTE: (1) The γ used for Pe with BFM is the IF carrier/noise ratio. For all others, γ is the signal/noise ratio at detector-input.

TABLE VIII-I (cont'd)

SUMMARY OF ERROR PERFORMANCE ANALYSIS

ALTERNATIVE	PROBABILITY OF ERROR FUNCTIONS (BIT OR SYMBOL)		
	COHERENT	NON-COHERENT	WITH RAYLEIGH FADING
DPSK	(Not Applicable)	$P_e = 1/2 \exp(-\gamma)$	$\overline{P}_e = \frac{1}{2 + 2\gamma_0}$
CHIRP	$P_e \geq 1/2 \operatorname{erfc}\sqrt{\gamma/2}$ $\simeq \frac{1}{\sqrt{2\pi\gamma}} \exp(-\gamma/2)$	---	---
Linear FM	(Not Applicable)	(Not Applicable)	(Not Applicable)

NOTE: See Index for definition of symbols.

TABLE VIII-II

SUMMARY OF ERROR RATE DATA

ALTERNATIVE	NON-FADING ENVIRONMENT		WITH RAYLEIGH FADING	
	Detector Input (S/N) = 14dB (γ = 14dB) Pe	RATING	(γ_o = 40dB) $\overline{Pe}$	RATING
OOK	Coherent : 2.14×10^{-4}	0.85	$\overline{Pe} \cong 2\times10^{-4}$	7.8
	Non-coherent: 9.5×10^{-4}	0.20		
BFM	Gaussian Region: 1.55×10^{-7} (β = .73) (γ_{IF} = 17.75 = 12.5 dB)	3.9	$\overline{P}_e\big\|_G \cong 2\times10^{-5}$; β = .73	10
	Spike Region: Pe = ? (β = 3.14) γ_{IF} = ? (NOTE 1)	-	$\overline{P}_e\big\|_S$ = ?	-
BFSK	Coherent : 3×10^{-7}	3.7	$\overline{P}_e\big\|_c \cong 5\times10^{-5}$	9.1
	Non-coherent: 1.9×10^{-6}	3.1	$\overline{P}_e\big\|_{nc} \cong 10^{-4}$	8.0
M-Ary FSK	Coherent : Not Applicable	-	$\overline{P}_{e_b} \leq 2\times10^{-4}$ (M = 4) (Bit Error)	7.8
	Non-coherent: 3.7×10^{-6} (M=4) ; (Bit Error)	2.8		
PSK	Coherent : 7.6×10^{-13}	10	$\overline{P}_e \cong 2.5\times10^{-5}$	9.8
	Non-coherent: (N/A)	-		
DPSK	Coherent : (N/A)	-	$\overline{P}_e \cong 5\times10^{-5}$	9.1
	Non-coherent: 6.7×10^{-10}	6.8		

NOTE 1: (1) γ_{IF} cannot be computed at this γ of 14 dB because receiver is not operating above threshold.

TABLE VIII-II (cont'd)

SUMMARY OF ERROR RATE DATA

ALTERNATIVE	NON-FADING ENVIRONMENT (γ = 14dB) Pe	RATING	WITH RAYLEIGH FADING (γ_0 = 40dB) $\overline{Pe}$	RATING
CHIRP	Coherent : $3x10^{-7}$	3.7	(Better than PSK)	10
	Non-coherent: (N/A)	0		
LINEAR FM	(N/A)	-	(N/A)	—

TABLE VIII-III

SUMMARY OF SPECTRUM UTILIZATION (BANDWIDTH)

ALTERNATIVE	BANDWIDTH			
	FUNCTION	BANDWIDTH/BIT RATE	RATING	
OOK	$B_I = 2/T$	2	10	
BFM	$B_c = 2\,B_R\,(\beta + 1)$ $\simeq 4\,B_R \;;\; \beta \leq 1$ $\simeq 10\,B_R \;;\; \beta \simeq 4$	$4 \;;\; \beta \leq 1$	7.5	3.8
		$10 \;:\; \beta \simeq 4$	0	
BFSK	$B_I = 2\,B_R\,(\beta + 1)$	$2\,(\beta + 1) \geq 8$ $(\beta \geq 3)$	2.5	
M-Ary FSK	$B_n = \frac{2^{(k+1)}}{k} = \frac{2M}{k}$ k = information bits per symbol M	$\frac{2M}{k} = 4$ (optimum)	1.25	
PSK	$B_n = \frac{c}{\log_2 M} = \frac{c}{k}$ $c \leq 2$	$2 \;\; (k = 1)$	10	
DPSK	$B_n = \frac{c}{\log_2 M} = \frac{c}{k}$. $c \leq 2$	$2 \;\; (k = 1)$	10	
CHIRP	$\Delta = \frac{D}{T}$ D = Dispersion	$D \cong 250$	0	
LINEAR FM	$B_I = 2f_m\,(\beta + 1)$	$2\,(\beta + 1) \geq 4$ $(\beta \geq 1)$	7.5	

TABLE VIII-IV

SUMMARY OF ECM/RFI

ALTERNATIVE	ECM/RFI SUSCEPTIBILITY	RELATIVE RATING
OOK	Good immunity against BB noise. Poor immunity to detectability, NB noise, and CW.	5
BFM	Approximately twice as good as OOK, on a power basis, for the same types of interference or jamming.	7
BFSK	Similar to BFM except for somewhat wider bandwidth requirements due to filter isolation; frequency instability effects may cause lesser performance.	6
M-Ary FSK	Similar to BFSK against noise interference. Intercept susceptibility may be slightly better than other NB methods.	7
PSK	One of the best if coherent processors can be used. Has minimum BW for a given data rate and therefore best against BB noise.	9
DPSK	Similar to PSK but not quite as good due to limitations of coherent processors.	8
CHIRP	Best method against all types of interference. Not optimized to any particular type.	10
LINEAR FM	Due to the 'Threshold Effect' in processing linear FM originals, this method is susceptible to all types of rf interference.	4

TABLE VIII-V

SUMMARY - COMPARISON OF MODULATION METHODS

METHOD / CRITERIA	OOK	BFM	BFSK	M-ARY FSK	PSK	DPSK	CHIRP	LINEAR FM	REMARKS
ERROR PERFORMANCE	0.20	3.9	3.1	2.8	10	6.8	3.7	-	
RAYLEIGH FADING	7.8	10	8.0	7.8	9.8	9.1	10	-	
ECM & RFI	5	7	6	7	9	8	10	-	
SPECTRUM UTILIZATION	10	3.8	2.5	1.25	10	10	0	-	
DEVELOPMENT RISK	10	10	10	8	5	8	7	-	
RANK									

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III, paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal, maximum, and minimum values of the weighting factors used are given in Table VIII-VI.

This initial analysis results in the following preference listing of the alternatives.

RANK	ALTERNATIVE		EVALUATION RATING
1	PHASE SHAFT KEYING	(E)	9.92
2	DIFFERENTIAL PSK	(F)	8.44
3	M-ARY FSK	(D)	5.09
4	ON-OFF KEYING	(A)	6.56
5	BINARY FM	(B)	6.51
6	CHIRP	(G)	5.94
7	BINARY FREQUENCY SHIFT KEYING	(C)	5.49

Since the least accurate figures in the calculation are accurate to two significant figures the evaluation rating given here is accurate to two significant figures.

7.2 Secondary Ranking Techniques. The procedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section are applicable. The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Table VIII-VIII.

7.3 Comparison of Results - Nominal Values. From Table VIII-VIII, the PSK (E) and Differential PSK (F) alternatives ranked first and second, respectively. In addition, E clearly ranked above F by a significant ER value for each calculation technique. Alternatives E and F were also grouped significantly above the remaining alternatives for all but the Logarithmic Technique, which exhibited virtually no difference in ER value between the second, third, and fourth rankings. However, a secondary grouping of alternatives based on the sum of all four techniques does appear, and consists of A, B, D, and G. Alternative D was the lowest ranked on a fairly consistant basis. An analysis of the evaluation score data, Table VIII-VII shows that each alternative, except E and F, contained at least one and sometimes two very low scores. Also, E and F scored the highest on the criterion which were most important; ECM/RFI and Spectrum Utilization.

TABLE VIII-VI

WEIGHTING FACTORS

CRITERION	NOMINAL WEIGHT	WEIGHT RANGE	
		MINIMUM	MAXIMUM
ERROR PERFORMANCE	.1716	.1000	.2400
RAYLEIGH FADING	.1316	.0800	.2500
ECM & RFI	.2926	.1900	.4000
SPECTRUM UTILIZATION	.2521	.1500	.3600
DEVELOPMENT RISK	.1521	.0600	.2000

TABLE VIII-VII

EVALUATION SCORES

CRITERIA	A.	B.	C.	D.	E.	F.	G.
I. ERROR PERFORMANCE (.1716)	.2	3.9	5.1	2.8	10.0	6.8	3.7
II. RAYLEIGH FADING (.1316)	7.9	10.0	8.0	7.8	9.8	9.1	10.0
II. ECM & RFI (.2926)	5.0	7.0	6.0	7.0	9.0	8.0	10.0
IV. SPECTRUM UTILIZATION (.2521)	10.0	3.8	2.5	1.25	10.0	10.0	.0
V. DEVEOLPMENT RISK (.1521)	10.0	10.0	10.0	8.0	5.0	8.0	7.0
EVALUATION RATING	6.56	6.51	5.49	5.09	8.92	8.44	5.94

ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

TABLE VIII-VIII

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS AND DIFFERENT WEIGHTING TECHNIQUES

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
A	6.56	3	7.47	3	3.89	6	8.82	4
B	6.51	4	7.00	5	6.01	3	8.38	5
C	5.49	6	6.11	6	4.82	4	7.72	6
D	5.09	7	5.82	7	4.01	5	6.75	7
E	8.92	1	9.08	1	8.70	1	9.46	1
F	8.44	2	8.51	2	8.37	2	8.86	2
G	5.94	5	7.23	4	.78	7	8.83	3

ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

8.0 SENSITIVITY ANALYSIS

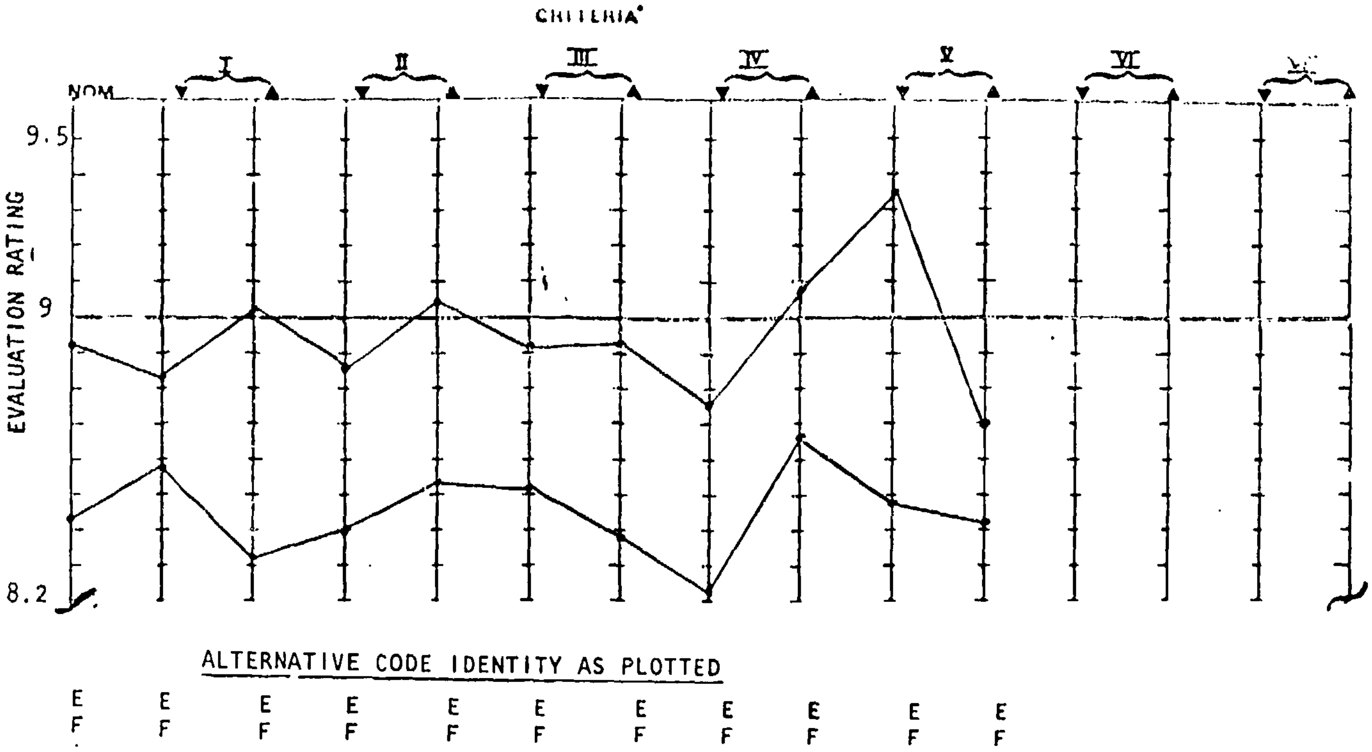
The procedures and discussions presented in Section III, paragraph 8.0 apply equally to this section except that the basic data presented in this section are applicable.

8.1 Sensitivity Study Using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 10 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 5 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately. The results of the additive weighting sensitivity study are plotted in Figure 8-8. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. From Figure 8-8 the top two alternatives retain their rank throughout the sensitivity study. Their rank is very stable. The outcome for the remainder of the alternatives is not as clear. However, the alternatives tend to cluster in groups, so that Figure 8-8 serves as a basis for group ordering when the ranking of individual alternatives is not clear. The resultant preference grouping derived from Figure 8-8 is listed below:

Group I	Phase Shift Keying (E)
Group II	Differential PSK (F)
Group III	Binary FM (B), On-Off Keying (A), Chirp (G)
Group IV	Binary Frequency Shift Keying (C)
Group V	M-ARY FSK (D)

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 44 sensitivity runs were made for the analysis. These runs showed that preference rankings for certain sensors remained constant while others shifted within certain bands. Tables VIII-IX through VIII-XIII show the resultant final scores and rank order of the alternatives as the indicated major criteria factor weights were varied, for the four analysis techniques.

The relationship among the evaluation scores for each alternative, the nominal weighting factors for the subcriteria and for the major criteria is as shown in Table VIII-VII. Table VIII-VI additionally includes the maximum and minimum values for the major criteria. When the five groupings were compared with the results obtained for RMS, Multiplicative and Logarithmic Weighting Techniques, Alternative E retained its first place ranking in all cases, usually by a significant ER margin. Alternative F ranked second in thirty-six of the forty-four cases and third in the remaining eight cases. Therefore, E and F clearly ranked first and second, respectively, by significant margins, and exhibits high stability. The remainder of the alternatives agreed fairly well with the results shown in Figure 8-8. The secondary group, comprised of A, B, and G, received a majority of their rankings alternately in the third, fourth, and fifth places, but no ranking stability was clearly established. However, the secondary group did stand above alternatives C & D, which also agreed with Figure 8-8.



ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

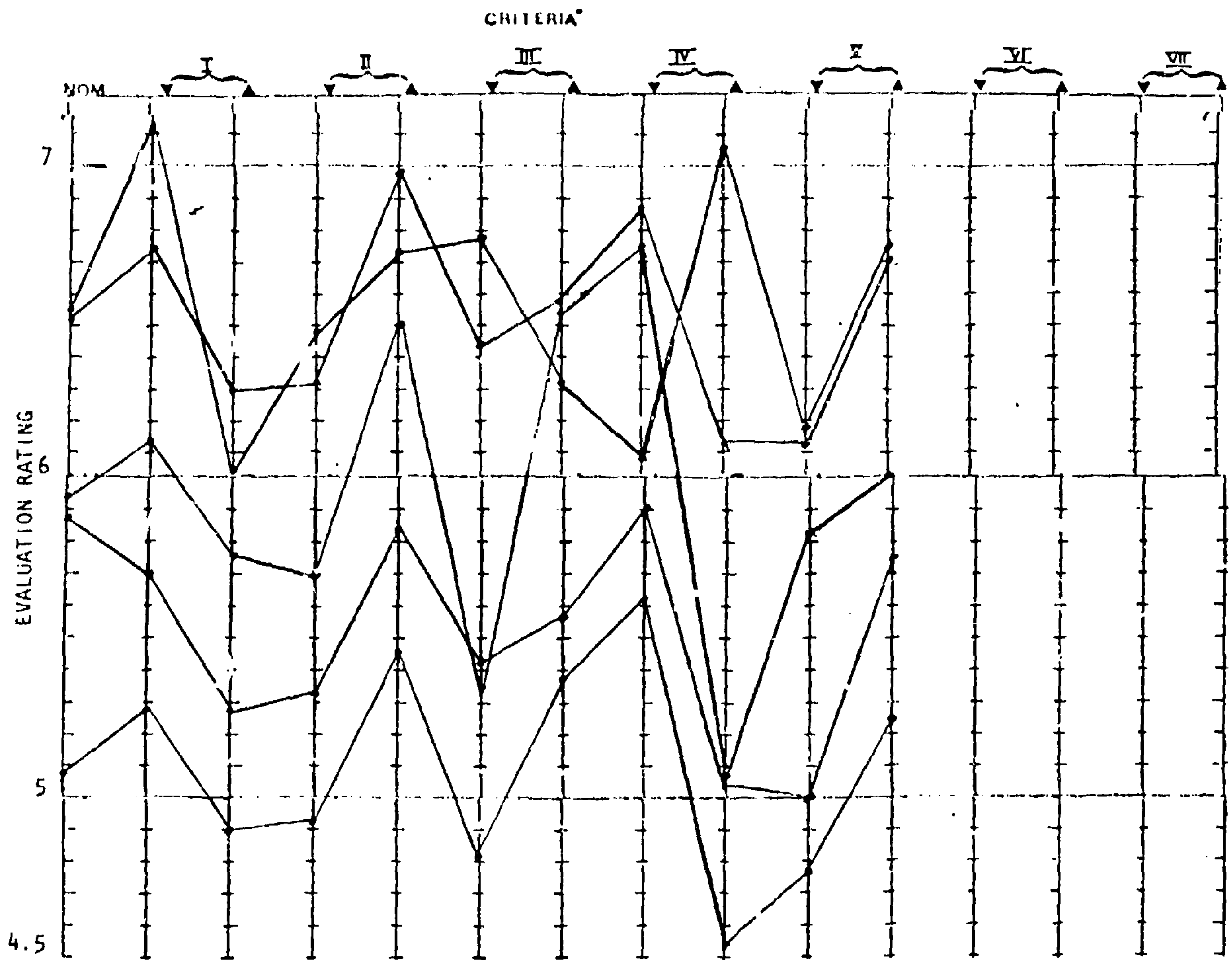
CRITERIA KEY

I. ERROR PERFORMANCE
II. RALEIGH FADING
III. ECM & RFI
IV. SPECTRUM UTILIZATION
V. DEVELOPMENT RISK

▼ MINIMUM WEIGHT
▲ MAXIMUM WEIGHT

FIGURE 8-8

ALTERNATIVE WEIGHTING VS WEIGHTING COMBINATION - ADDITIVE WEIGHTING



ALTERNATIVE CODE IDENTITY AS PLOTTED

A	A	B	A	B	A	B	B	A	A	A
B	B	A	B	A	B	G	G	B	B	B
G	G	G	G	G	C	A	A	G	G	G
C	C	C	C	C	G	C	C	C	C	C
D	D	D	D	D	D	D	D	D	D	D

ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

CRITERIA KEY

I. ERROR PERFORMANCE
II. RALEIGH FADING
III. ECM & RFI
IV. SPECTRUM UTILIZATION
V. DEVELOPMENT RISK

▲ MAXIMUM WEIGHT ▼ MINIMUM WEIGHT

FIGURE 8-8 (Continued)

TABLE VIII-IX

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING ERROR PERFORMANCE FACTOR

ALTER- NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	7.11	3	7.78	3	5.12	4	8.94	4
B	6.74	4	7.20	5	6.23	3	8.50	5
C	5.70	6	6.31	6	5.01	5	7.84	6
D	5.28	7	6.01	7	4.14	6	6.86	7
E	8.83	1	9.00	1	8.60	1	9.41	1
F	8.59	2	8.65	2	8.52	2	8.95	3
G	6.14	5	7.45	4	.68	7	8.95	2
MAX								
A	6.03	4	7.15	3	2.99	6	8.70	4
B	6.30	3	6.79	5	5.80	3	8.27	5
C	5.29	6	5.92	6	4.65	4	7.60	6
D	4.90	7	5.63	7	3.69	5	5.63	7
E	9.01	1	9.16	1	8.80	1	9.52	1
F	8.31	2	8.39	2	8.23	2	8.76	2
G	5.76	5	7.00	4	.89	7	8.71	3

WEIGHTS USED IN THESE RUNS

MIN : = .1000; = .1430; = .3179; = .2739;
= .1652;

MAX : = .2400; = .1207; = .2684; = .2313;
= .1395;

ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

TABLE VIII-X

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING RAYLEIGH FADING FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	6.49	3	7.45	3	3.73	6	8.87	2
B	6.31	4	6.78	5	5.83	3	8.19	5
C	5.34	6	5.98	6	4.68	4	7.70	6
D	4.93	7	5.68	7	3.06	5	6.65	7
E	8.87	1	9.04	1	8.64	1	9.44	1
F	8.40	2	8.48	2	8.33	2	8.84	3
G	5.70	5	7.03	4	.67	7	8.72	4
MAX								
A	6.73	4	7.51	4	4.27	6	8.72	5
B	6.99	3	7.48	5	6.44	3	8.74	4
C	5.83	6	6.40	6	5.17	4	7.76	6
D	5.46	7	6.12	7	4.39	5	6.95	7
E	9.04	1	9.18	1	8.85	1	9.51	1
F	8.53	2	8.60	2	8.47	2	8.89	3
G	6.50	5	7.66	3	1.11	7	9.06	2

WEIGHTS USED IN THESE RUNS

MIN ; = .1818; = .0800; = .3100; = .2671;
= .1611;

MAX ; = .1462; = .2500; = .2527; = .2177;
= .1314;

ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

TABLE VIII-XI

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING ECM & RFI FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	6.79	3	7.76	3	3.75	5	9.01	2
B	6.44	4	7.00	4	5.87	3	8.51	5
C	5.42	5	6.13	6	4.67	4	7.86	6
D	4.81	7	5.62	7	3.70	6	6.71	7
E	8.91	1	9.10	1	8.66	1	9.52	1
F	8.51	2	8.59	2	8.43	2	8.95	3
G	5.35	6	6.73	5	.54	7	8.55	4
MAX								
A	6.32	5	7.15	4	4.04	6	8.60	4
B	6.59	3	7.00	5	6.15	3	8.24	5
C	5.57	6	6.10	6	4.99	4	7.56	6
D	5.38	7	6.01	7	4.36	5	6.79	7
E	8.93	1	9.07	1	8.75	1	9.40	1
F	8.38	2	8.64	2	8.31	2	8.75	3
G	6.56	4	7.71	3	1.15	7	9.08	2

WEIGHTS USED IN THESE RUNS

MIN : = .1965, = .1507, = .1900, = .2887, = .1742,

MAX : = .1455, = .1116, = .4000, = .2138, = .1290,

ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

TABLE VIII-XII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING SPECTRUM UTILIZATION FACTOR

ALTERNATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	6.09	5	7.05	5	3.42	6	8.55	5
B	6.88	3	7.35	4	6.39	3	8.56	4
C	5.90	6	6.45	6	5.28	4	7.90	6
D	5.61	7	6.18	7	4.70	5	6.93	7
E	8.77	1	8.95	1	8.54	1	9.37	1
F	8.23	2	8.29	2	8.17	2	8.60	3
G	6.75	4	7.70	3	1.95	7	9.02	2
MAX								
A	7.06	3	7.88	3	4.45	4	9.06	3
B	6.12	4	6.63	5	5.62	3	8.17	5
C	5.06	6	5.74	6	4.39	5	7.50	6
D	4.53	7	5.40	7	3.39	6	6.53	7
E	9.08	1	9.22	1	8.88	1	9.55	1
F	8.67	2	8.74	2	8.59	2	9.09	2
G	5.08	5	6.68	4	.30	7	8.61	4

WEIGHTS USED IN THESE RUNS

MIN : = .1950; = .1496; = .3325; = .1500; = .1729;

MAX : = .1463; = .1126; = .2504; = .3600; = .1302;

ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

TABLE VIII-XIII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING DEVELOPMENT RISK FACTOR

ALTER- NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	6.19	3	7.14	4	3.51	6	8.61	4
B	6.13	4	6.59	5	5.68	3	8.02	5
C	5.00	6	5.53	6	4.46	4	6.94	6
D	4.77	7	5.53	7	3.72	5	6.51	7
E	9.35	1	9.02	1	9.24	1	9.61	1
F	8.49	2	8.57	2	8.41	2	8.92	3
G	5.83	5	7.25	3	.62	7	8.94	2
MAX								
A	6.75	3	7.63	3	4.10	6	8.92	2
B	6.71	4	7.20	5	6.18	3	8.54	5
C	5.75	6	6.40	6	5.03	4	8.01	6
D	5.25	7	5.96	7	4.17	5	6.86	7
E	8.70	1	8.00	1	8.43	1	9.38	1
F	8.42	2	8.49	2	8.35	2	8.82	3
G	6.00	5	7.21	4	.89	7	8.77	4

WEIGHTS USED IN THESE RUNS

MIN ; = .1902; = .1459; = .3244; = .2795;
= .0600;

MAX ; = .1619; = .1242; = .2761; = .2379;
= .2000;

ALTERNATIVE KEY

A. ON-OFF KEYING
B. BINARY FM
C. BINARY FREQUENCY SHIFT KEYING
D. M-ARY FSK
E. PHASE SHIFT KEYING
F. DIFFERENTIAL PSK
G. CHIRP

9.0 CONCLUSIONS

The analysis indicates that PSK is [illegible] method of digital data modulation of all methods considered. In order for PSK to outperform other methods, a coherent or matched filter receiver must be used. Under certain conditions a coherent system may be approximated, given sufficient time for phase and frequency synchronization at the receiver. Likewise, a matched filter processor may be accomplished for brush type digital signals using a SWD. Unfortunately, SWD's are only applicable to wideband type signals. Since the analysis was made, independent of the type of transmission techniques (wideband or narrowband), and since a narrowband technique was recommended as a result of engineering analysis 1, the results of the engineering analysis must be evaluated in light of the narrowband transmission technique. Consequently, PSK tends to lose its ranking with a narrowband system such as REMBASS will use. Similar conclusions are applicable to other methods which require a coherent processor or matched filter receiver. These are: a) differential PSK; and b) Chirp. On-off Keying (OOK) is ranked rather high, if one is able to insure a specified minimum $(S/N)_{min}$ at the receiver, determined by the required message bit error rate. If this $(S/N)_{min}$ cannot be insured, the performance of the system degrades drastically. Since the REMBASS DTS cannot be insured of a given receiver (S/N), using OOK modulation is not considered to be advisable. Adaptive threshold techniques may be incorporated in the receiver in some cases but this would impact on message structure and message duration. It is believed that sufficient weight was not given to error performance in the analysis and too much weight was given to spectrum utilization. Changing these weights would easily reverse the ranking of OOK vice BFM or BFSK.

10.00 RECOMMENDATIONS

Binary FM and Binary FSK differ in the receiver more than in the transmitter. In fact, a BFM receiver can receive a BFSK modulated signal. A BFM receiver is used if both analog and digital data are transmitted. If only digital data is transmitted a BFSK dual filter receiver will degrade more gracefully with decreasing (S/N) than BFM, therefore, since it appears that REMBASS will not transmit analog data, a BFSK modulation of digital data is recommended.

SECTION IX

ENGINEERING ANALYSIS 8
MESSAGE TYPES

1.0 SUMMARY

This analysis addresses the problem of transmitting analog data through the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated against a specific set of criteria; signal quality, power requirements, spectrum utilization, equipment complexity and equipment costs. The analysis concludes that analog data should not be digitized prior to transmission.

2.0 INTRODUCTION

This engineering analysis will evaluate methods of transmitting analog sensor data over the DTS. A comparison will be made between digital techniques and straightforward analog transmission by linear frequency modulation (FM). Both Delta Modulation (DM) and Pulse Code Modulation (PCM) will be considered as digital techniques. These alternatives are defined in paragraph 4.0 and various criteria, by which the techniques may be compared, are defined in paragraph 5.0. In paragraph 6.0 the technical evaluation will be made.

3.0 STATEMENT OF THE PROBLEM

The REMBASS Material Need (MN) currently specifies that some acoustical sensors will be a part of the inventory and that this acoustic (analog) data will be provided to the SRU in addition to other digital data. Considering that much of the sensor data may be transmitted over repeater links consisting of several repeaters in tandem, the problem of getting good quality analog data to the SRU becomes quite a challenge for the DTS. This engineering analysis will consider alternate means of accomplishing this.

4.0 ALTERNATIVES

Digital messages will be used to transmit the digital sensor data to the SRU either directly or via one or more repeaters. The analog data may be transmitted either by analog messages (linear FM) or it may be digitized and transmitted as digital messages, in a manner consistent with the digital data. Therefore, the alternatives are:

a) Digital only messages in which the analog data is quantized and transmitted in digital form; and b) Digital and analog messages in which the digital data is transmitted by one method and the analog data is transmitted by another.

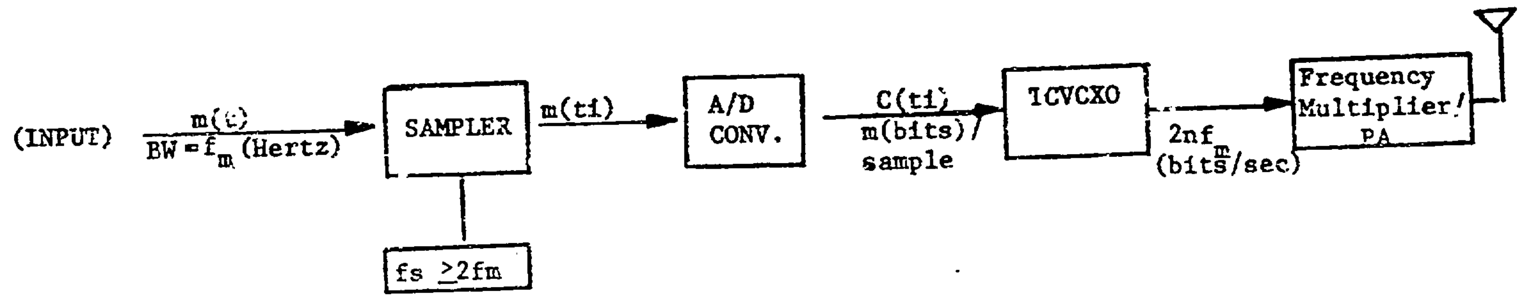
Since by both alternatives, the digital data messages are assumed to be transmitted and relayed by identical means, the alternatives become merely a comparison between the digitized analog message transmission in a digital system versus the analog message transmission of a dual digital/analog system.

4.1 Digitized Analog Data Transmission. Two digital techniques will be considered for transmitting digitized analog data: a) DM; and; b) PCM. Modifications of these techniques may be considered in a more detailed design analysis if a digitized system is selected (e.g., Delta-Sigma Modulation ($\Delta\Sigma M$) in lieu of DM and Delta-PCM for PCM), but these refinements are not considered necessary for the present evaluation. The term "Modulation" used with each of these techniques does not apply to the method of modulation applied to the carrier for transmitting the digital data, which is applied to the modulator. Either technique may use PSK, FSK, etc., as a modulation method. Instead of performing a comparative evaluation of these two digital techniques and using the selected one to compare with the analog alternative, they will be considered as independent alternatives for the evaluation. The reason for this decision is that the criteria for comparison would be the same in each case, therefore, there is no need to evaluate the digital alternatives separately before comparing with the analog alternative.

4.1.1 Pulse Code Modulation (PCM). A block diagram of a PCM transmitter is shown in Figure 9-1. The analog input data is represented by m(T) which is band limited to fm (Hertz). The analog signal is quantized by a sampler at a rate f_s which must be a minimum of 2 fm, but is always greater to avoid aliasing problems. The quantized data is converted to digital code groups of n bits/sample which then are used to modulate the carrier by PSK, FSK or some selected method. The digital bit rate will be a minimum of 2nfm bits/sec. The PCM receiver is shown in Figure 9-2. The modulated signal is received and converted to IF. A matched filter may be used to recover the digital data. The code groups are synchronized and converted back to an analog signal representing the original data. The PCM repeater is basically a combined receiver and transmitter with the additional requirement for synchronization and storage for digital data if a Store and Forward (S&F) repeater is used. This storage requirement can become prohibitively large if long duration analog signals are transmitted. If real time repeaters are used, the storage is not required. A PCM repeater is shown in Figure 9-3.

4.2 Direct Analog Data Transmission. The method selected for direct analog data transmission is linear FM of the carrier by the baseband analog data. The FM index ($\beta = \frac{\Delta f}{f_m}$) is a parameter which may be used in a trade-off between transmission bandwidth and transmitter (carrier) power. Figure 9-7 is a block diagram representation of the modulation and transmission function of a sensor, etc., which transmits analog data directly by linear modulation (modulation directly proportional to amplitude of analog signal) of the carrier. The simplicity of this technique is obvious. A similar block diagram is shown in Figure 9-8 for the receiver. The output of the receiver IF limiter is applied to a fm discriminator where the analog modulating signal is recovered. It is passed through a low pass filter to limit the noise to the baseband bandwidth. The output signal is a noisy reproduction of the input and the quality is dependent primarily on the carrier-to-noise ratio (C/N) at the input to the receiver. A repeater block diagram for the analog modulated carrier is shown in Figure 9-9. It is assumed that the baseband signal is not recovered in the repeater, therefore, an IF repeater is used. The repeater must operate in real time. Consequently the up-converter generates a modulated frequency f_2 which is sufficiently separated from f_1 that no degrading interference results. It is to be noted that the up-converter changes the frequency but not the modulation index, B_1.[1/] Due to the added noise from the receiver and converter, the output (C/N) will be degraded. In addition, instabilities in the local TXCO's may cause a reduction in permissible dynamic range of the original analog signal. These characteristics of repeaters tend to limit the quality of analog data which may be relayed over large distances where more than one repeater must be used.

1/ "Signal Processing, Modulation and Noise", American Elsevier Publishing Co., Inc., N.Y., 1971, J. A. Betts.



m(t) = Analog baseband signal (bandlimited)

FIGURE 9-1

DIGITIZED ANALOG TRANSMISSION (PCM)

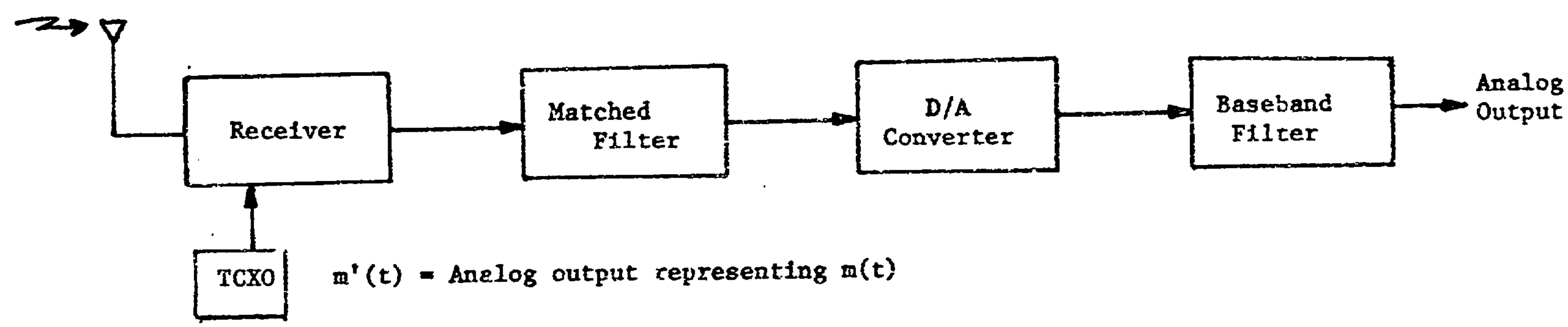


FIGURE 9-2

DIGITAL RECEIVER (PCM)

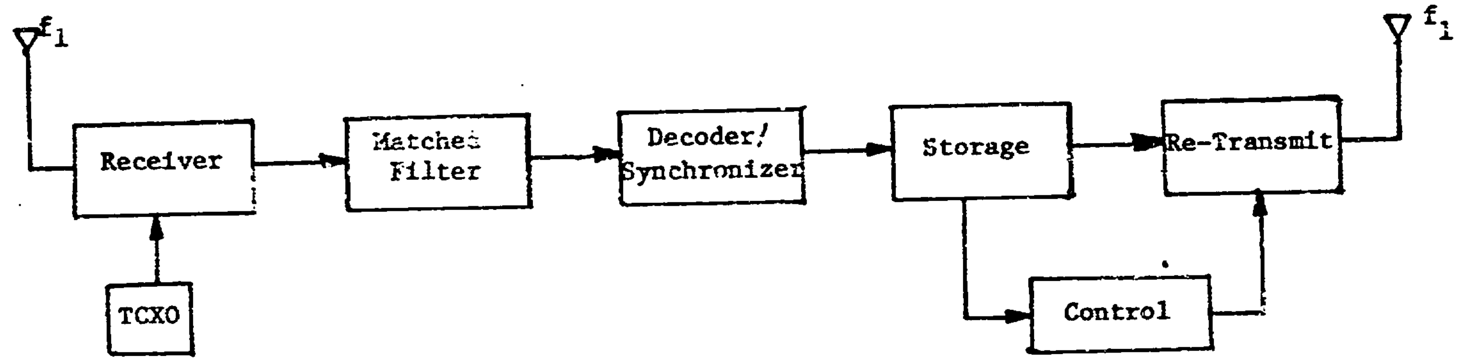
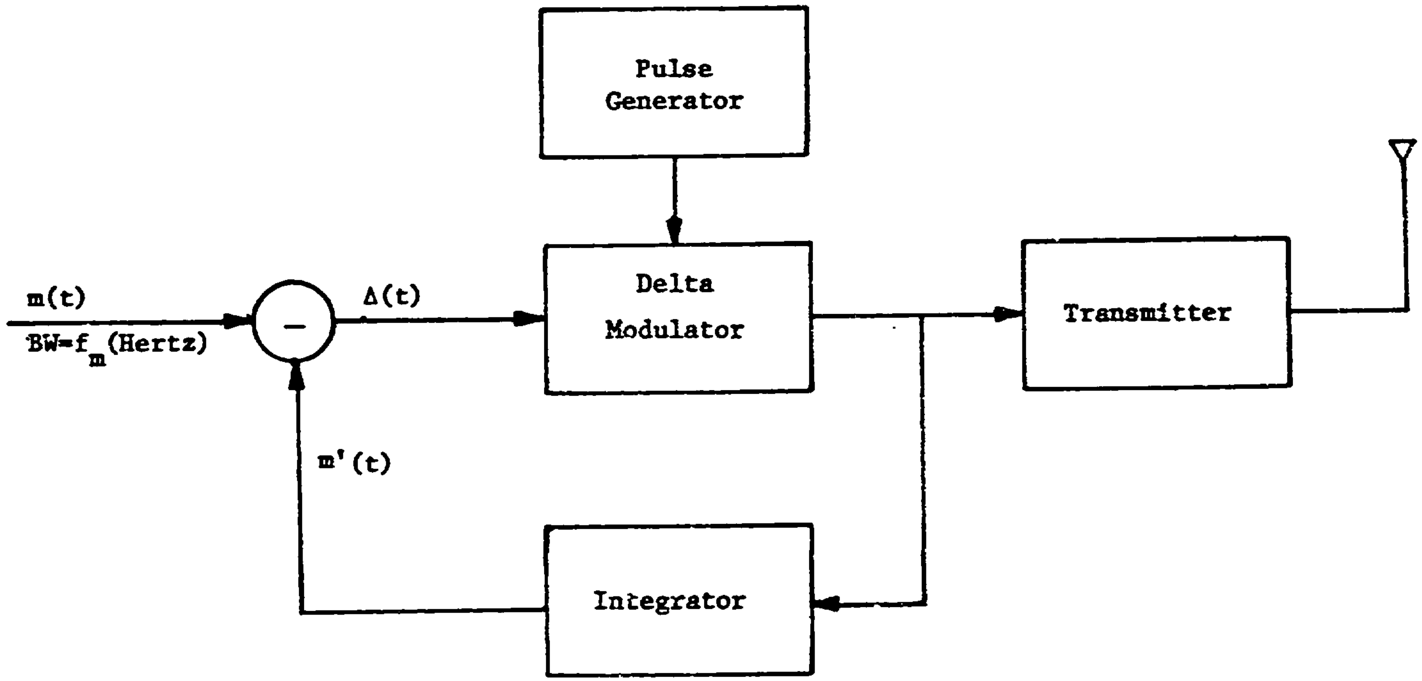


FIGURE 9-3

DIGITAL REPEATER (PCM) (STORE-AND-FORWARD)

4.1.2 Delta Modulation (DM). A block diagram of a transmitter for digital transmission of analog data by DM is shown in Figure 9-4. The band-limited analog signal, m(t), is compared with a feedback replica, m'(t), which is the integrated output of the DM. The error signal, $\Delta(t)$ is applied to the DM and the output from the DM (+ 1 or -1) is determined by the sign of $\Delta(t)$ at the sampling instant. A single binary digit (bit) is transmitted at a rate consistent with the quantization noise requirement at the receiver output, and may be several kilobits per second. A block diagram of a DM receiver is shown in Figure 9-5. A matched filter processor may be assumed and its output will be a non-return-to-zero (NRZ) binary waveform representing the binary sequence from the DM. This is integrated and filtered to provide the analog output representative of the original analog input signal. The relative quality of this output signal will depend on the signal power at the receiver input, the input and receiver noise, and the sampling frequency of the delta modulator. A typical DM repeater block diagram is given in Figure 9-6. Since this is to be a digital repeater, the acquired analog signal is not reconstructed in the repeater; only the binary (NRZ) waveform is regenerated. This digital data is stored during the receiving interval and retransmitted at the end of the incoming message. The amount of storage required depends upon the amount of analog data needed during a single transmission interval. The storage required will be comparable for DM and PCM in any case, and it may be the factor which determines the efficacy of the digital alternative versus direct analog transmission.



$\Delta(t) = m(t) - m'(t)$

FIGURE 9-4

DIGITIZED ANALOG TRANSMISSION (DELTA MODULATION)

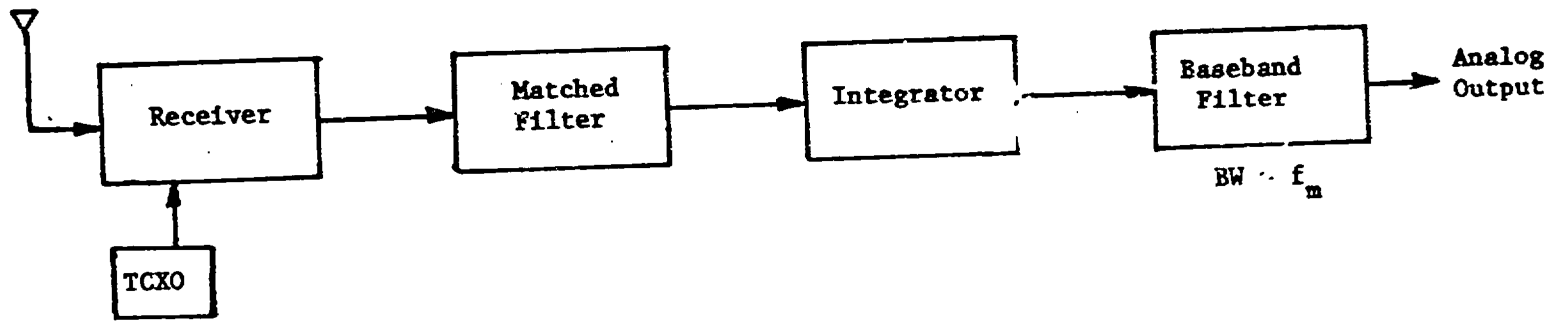


FIGURE 9-5

DIGITAL DELTA MODULATION RECEIVER

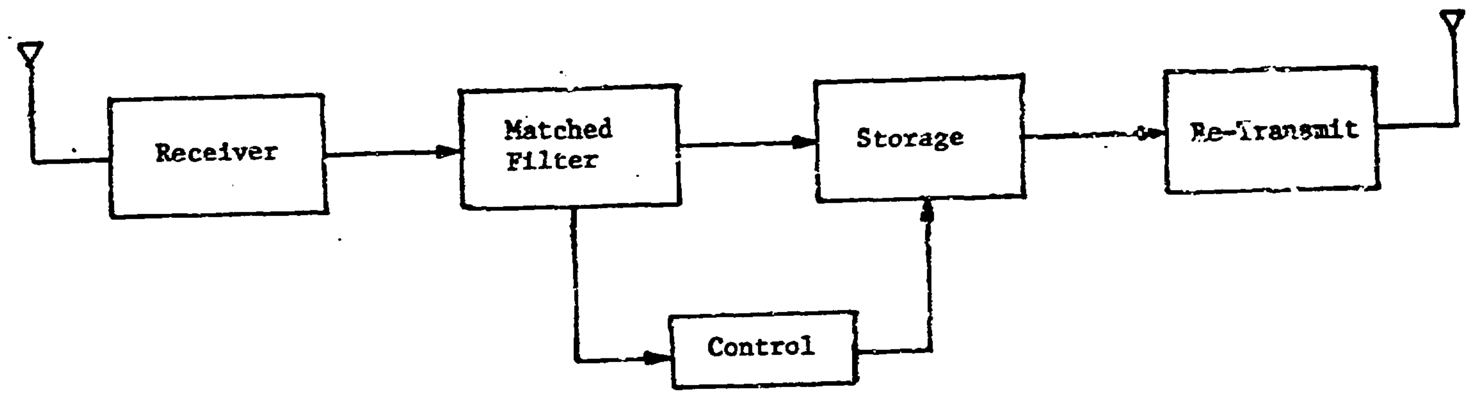


FIGURE 9-6

DIGITAL DELTA MODULATION REPEATER

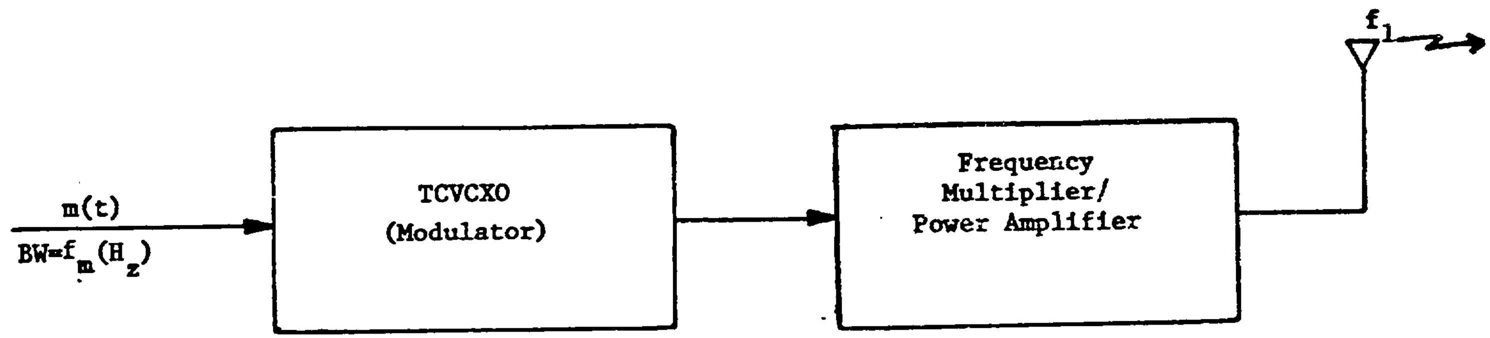


FIGURE 9-7

LINEAR ANALOG MODULATION (FM)

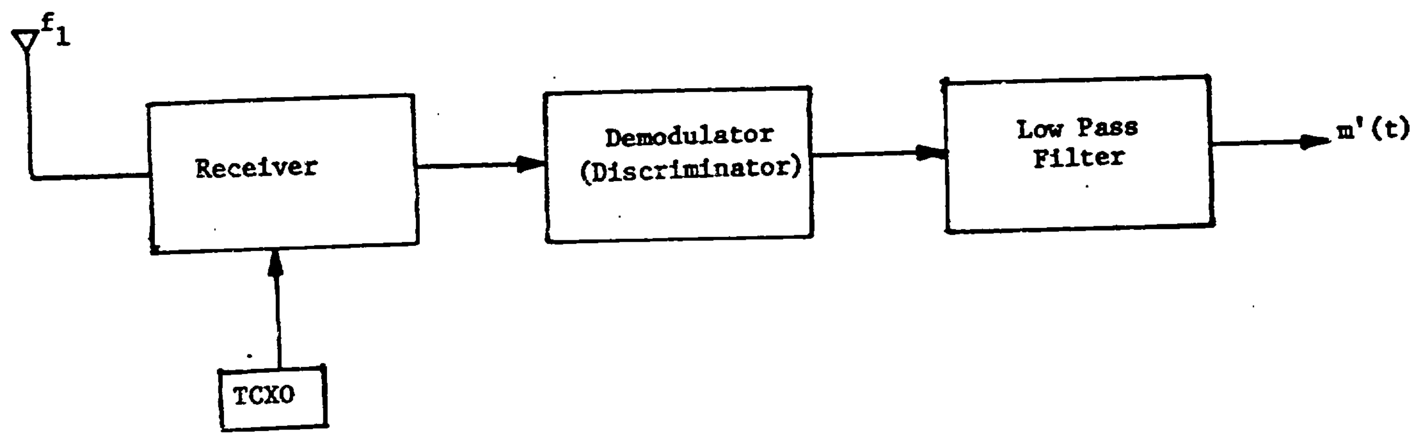


FIGURE 9-8

RECEIVER FOR ANALOG (LINEAR) MODULATED CARRIER

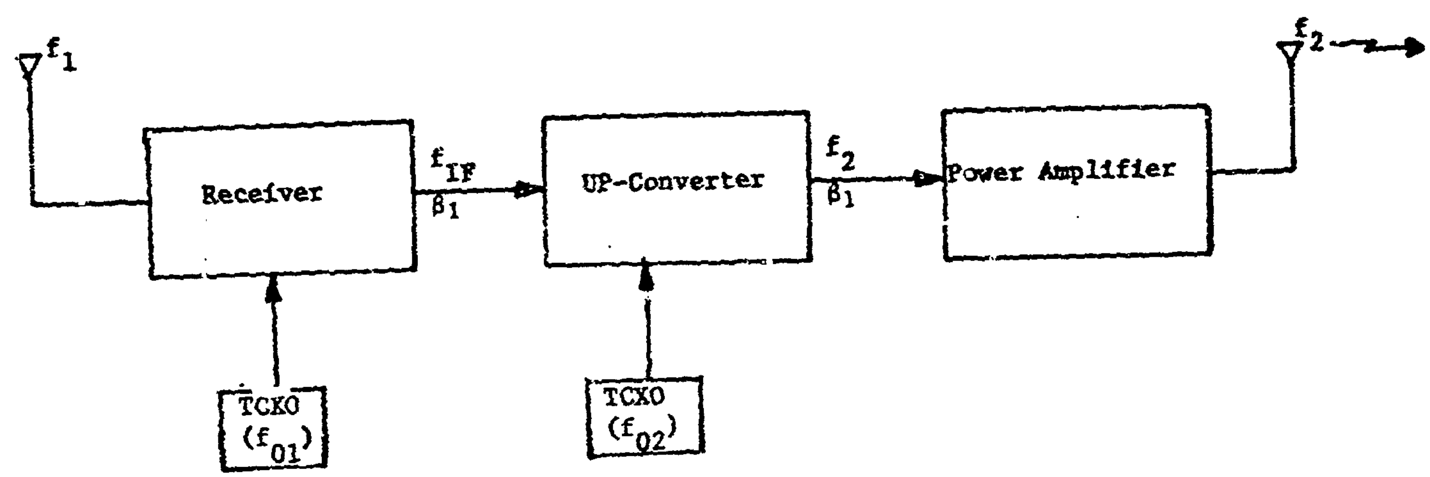


FIGURE 9-9

IF REPEATER FOR ANALOG MODULATED CARRIER

5.0 CRITERIA

The criteria which will be used in evaluating the relative merits of transmitting analog sensor data by linear FM or by A/D conversion and digital transmission are defined below. A data link which may include one or more repeaters between the data source (sensors) and the readout station (SRU) adds a dimension to this subject which may have overriding implications. The degree to which repeaters may impact the decision against digitized analog data will depend upon the amount of analog data (message duration) which is required at the SRU. If the data is to be used to perform a spectral analysis only, then only small amounts would be needed during one transmission request. However, if the analog data is to be evaluated by human operators listening to identify sounds (targets) a much greater quantity of data would be required, and this fact would seriously impact the decision between alternatives, regardless of the results of other criteria evaluation. Consequently, the final decision must be reserved until the SRU operating procedures is established.

5.1 Relative Signal Quality (S/N) out. Given a signal of a specified quality at the source, this criterion will compare the alternatives in terms of the degradation in signal quality as it is communicated (transmitted) by the methods previously defined. A measure of this quality will be the ratio of signal output power to noise power, from whatever source the noise may originate.

5.2 Relative Power Requirements. This is the radiated (transmitted) power required by the alternative methods to provide a specified signal-to-noise (S/N) ratio at the receiver output (i.e., analog signals out of receivers). Range is assumed fixed, although system bandwidth may be different due to different bandwidth requirements of the alternatives.

5.3 Spectrum Utilization. This criterion is related to the transmission bandwidth required by the alternatives. The larger the bandwidth required for a given baseband data bandwidth, the less efficient is the alternative for spectrum utilization.

5.4 Equipment Complexity. This criterion provides a means of comparing the alternatives in terms of the degree of complexity of the transmitter and receiver circuitry necessary to get the analog data from source to user. In addition, impact of a S&F digital mode of operation in the repeater(s) will be investigated. In particular, the amount of digital data storage will be determined for specified durations of analog signals.

5.5 Relative Costs. The relative costs of equipments for the alternatives should be related to the increased equipment complexity of the alternatives. This criterion will provide an additional measure of comparison in a semi-quantitative way.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 General. Each of the alternatives defined in paragraph 4.0 will be analyzed separately in terms of the criteria of paragraph 5.0. In general, the performance will be considered in terms of the ideal or theoretical maximum for a given parameter, recognizing that in practice this ideal is not likely to be achieved. For example, a communication channel which has an assigned bandwidth (W) theoretically has a channel capacity of 2W independent pulses per second although, in practice this capacity is never even approximated. 2/ This assumption should not severely influence or jeopardize the comparative evaluation of alternatives, since all will be similarly treated.

6.2 Parameter Values. In order to make a quantitative comparison and evaluation of the various alternatives, certain parameter values must be specified. For the digital alternatives it is assumed that the (S/N) at the UCR will be limited by qualtization noise, (i.e., the (S/N) at each detection point is such that detection errors do not contribute to the final (S/N). For the analog alternative it is assumed that the noise degradation through a link of four repeaters is a maximum of 6 dB. Therefore, the input (S/N) for the analog system must be greater than that for the digital alternatives. The following parameter values and operational requirements will be assumed:

a) $(S/N)_{out} \cong$ 26 dB (terminal receiver output)
b) f_m = 2 kHz (baseband bandwidth)
c) T_m = 10 sec (analog message duration)
d) No encryption of data
e) No time multiplexing of signals
f) System is power limited
g) Data relayed thru up to 4 repeaters
h) ECM protection not required for analog data

The assumed output (S/N) of 26 dB is based on the fact that a good quality signal is required in order to distinguish between sounds which may be very similar. This quality signal is not necessarily required for speech since the listener is able to interpolate unintelligible parts. The 2 kHz bandwidth is also based on the assumption that the analog data will be something other than, or in addition to, speech signals.

2/ "The Philosophy of PCM, "Proc. IRE 1948, B. Oliver, J. Pierce, S. Shannon.

6.3 Alternatives.

6.3.1 Digital; DM.

6.3.1.1 Relative Signal Quality, (S/N). The resultant output (S/N) is affected by detection error noise and quantization noise for a DM system. That is:

$$(S/N)_R = \frac{S}{N_Q + N_E} \tag{1}$$

where N_Q = quantization noise

N_E = detection error noise

If the (C/N) in the receiver is high enough such that the detection error probability is about 10^{-4} or less, only quantization noise effects the output signal quality. Therefore, it is necessary to choose a sample rate at the A/D converter, such that the required $(S/N)_Q$ will be met for the bandwidth of the source data. The quality of the signal can be maintained through several repeaters without serious degradation due to the regeneration action of the digital system.

6.3.1.2 Relative Power Requirements. The (C/N) required in the receiver for "threshold" operation is a measure of the relative power requirements. This (C/N) was defined in the previous section as that value which gives an error probability of 10^{-4} or less. With DPSK modulation/detection, this requires a $(C/N)_{IF}$ of about 9.3 dB as determined from the relation:

$$P_{e/DPSK} = 1/2\ e^{-(C/N)} \tag{2}$$

6.3.1.3 Spectrum Utilization. The bandwidth per unit bit rate for DM with BDPSK modulation was given as 2 in engineering analysis 7. The required transmission bandwidths, neglecting frequency tolerances, etc. are given by:

$$B_{DM} = 2f_s \tag{3}$$

f_s = sampling rate of the Delta modulator

Since it is assumed that the (C/N) at the receiver is above threshold, f_s may be determined from the required $(S/N)_Q$ given in 6.2. The relation between $(S/N)_Q$ and f_s is given as:

$$(S/N)_Q \leq \frac{3}{64}\left(\frac{f_s}{f_m}\right)^3 \tag{4}$$

f_s = sampling rate

f_m = highest frequency with peak amplitude of input signal

With speech it has been found experimentally 3/ that a DM system will not overload provided an 800 Hz sine wave can be transmitted whose amplitude is equal to the peak instantaneous amplitude of the signal to be transmitted. This is not necessarily true with other types of analog signals, and therefore f_m must be assumed to be the highest baseband frequency of the signal to be transmitted. Assuming f_m is 2000 Hz, f_s is found to be:

$$f_s = f_m \sqrt[3]{\frac{64}{3} (S/N)_Q} \qquad (5)$$

f_m = 2000 Hz

$(S/N)_Q$ = 26 dB = 400 ratio

f_s = 40 Kb/sec

Therefore, from (3) the required bandwidth is:

$$B_{DM} = 2f_s = 80 \text{ kHz} \qquad (6)$$

6.3.1.4 Equipment Complexity. As compared to PCM, DM is a much simpler system to implement, whereas, compared to linear FM it is somewhat more complex, especially if S&F repeaters are used. The complexity of S&F repeaters is a direct result of the sampling rate and the duration of analog signals which must be transmitted. The quantity of digital data storage required may be estimated as follows:

f_s = 40 Kb/sec

$T_m \approx$ 10 sec

Total Bits/msg = $f_s T_m$

= 400,000 bits

Even with LSI of digital data storage the space required for this much memory storage is not insignificant.

3/ "Signal Processing, Modulation and Noise," T.A. Betts, American Elsevier Publishing Co., Inc.

6.3.1.5 Relative Costs. In view of the lesser complexity of equipment as compared to PCM, the DM system should be the least expensive of the digital systems. It would be somewhat more expensive than linear FM by virtue of the analog-to-digital conversion equipment required in the sensor, as well as the digital storage required in repeaters. With a required storage of 400,000 bits, the added cost would be considerable. Even at a cost of a 0.2¢ per bit, the added storage cost would increase the cost of a DM repeater by $800. 4/

6.3.2 Digital; Pulse Code Modulation (PCM).

6.3.2.1 Relative Signal Quality, (S/N). As with DM there are two types of noise to be considered in PCM: a) detection error noise; and b) quantization noise. Detection error noise will be more significant in PCM than in DM due to the different weights assigned to the bits in a PCM code word. A bit error will cause different amounts of noise depending upon what position in the code word the error occurs. Only at the least significant bit of the PCM code word will the error be equally effective in PCM and DM. For reasonably low error rates ($P_e < 10^{-2}$) the relation between $(S/N)_E$ due to detection errors and detection error probabilities is given by: 5/

(7) $$(S/N) = \frac{1}{4P_e}$$

P_e = probability of error or error rate

$(S/N)_E$ = signal-to-error noise power ratio

If the output (S/N) is to be primarily a function of the quantization noise then the error rate due to noise must be of the order of 10^{-5}. This requires a (C/N) of about 10.2 dB. The $(S/N)_Q$ is related to the number of bits per PCM code group, n, as:

(8) $$(S/N)_Q = (3/2)2^{(2n)}$$

$$n = 4$$

$$(S/N)_Q = 384 \text{ ratio} = 25.8 \text{ dB}$$

A 4 bit code word will therefore provide very close to the desired signal quality.

4/ Computer Memory Technology Forecast - 1985, The MITRE Corporation, MTR-6483, 31 Aug. 1973.

5/ "Analog-FM vs. Digital-FSK Transmission," IEEE Trans. on Comm. Tech. Vol 14, No. 3, 1966, James W. Whelan.

6.3.2.2. Relative Power Requirements. The required receiver (C/N) as determined in 6.3.2.1 above is about 10.2 dB. This is almost 1 dB greater than that required for DM.

6.3.2.3 Spectrum Utilization. The minimum bandwidth required to transmit PCM analog data is related to the highest frequency of the analog data and the code bits per sample as follows:

(9) $$B_{PCM} \geq 2f_m n$$

Where $f_m = 2000$ Hz

$n = 4$ bits/code

therefore

(10) $$B_{PCM} \geq 2x2x10^3x4$$

$$= 16x10^3 Hz$$

and PCM is seen to be superior to DM in utilizing the RF sectrum, for equal output $(S/N)_Q$.

6.3.2.4 Equipment Complexity. The digital PCM requires quantization of the analog signal and digital encoding prior to modulation and transmission of the data. This plus the digital-to-analog (D/A) conversion at the receiver makes the PCM somewhat more complex than the digital DM technique and considerably more complex than linear FM. In the S&F repeater, as with DM, considerable digital storage will be required although not so much as with DM, since the data rate is 16 Kb/s the storage required is:

(11) Digital Storage = 16 Kb/s x 10 sec

= 160,000 bits

6.3.2.5 Relative Costs. The sensors and receivers will be somewhat more expensive than comparable DM units but this may be offset by the lesser cost of digital storage in the repeater. It will depend on the relative number of equipments used. At 0.2¢/bit the added cost of digital storage in the epeater is approximately $320 as compared to $800 for DM.

6.3.3 Direct Analog (Linear FM) Transmission.

6.3.3.1 Relative Signal Quality. The primary disadvantage of linear FM for analog data transmission is the signal quality degradation that occurs through repeaters. As the number of repeaters in a link increases, the quality of the analog signals is degraded due to the added noise from each repeater receiver. To counteract this difficulty, either the signal power is increased at the source (sensor transmitter), the range is reduced, or transmission bandwidth is expanded by increasing the modulation index, β. Since range requirements are fixed, we have a tradeoff between transmission bandwidth and power to achieve the quality at the final receiving point after being passed through the maximum number of repeaters in a relay link.

6.3.3.2 Relative Power Requirements. Allowing for a 6 dB loss through the maximum number of repeaters expected in a relay link, a $(S/N)_o$ at the first receiver of about 32 dB will be required to insure a 26 dB (S/N) at the final receiver output. Since we have a possible tradeoff between power and RF bandwidth, and since power sources are limited, we will choose a β to give the $(S/N)_o$ of 32 dB with a (C/N) just above threshold, since this will be the minimum power FM system. 6/ The relation between $(C/N)_{IF}$ and the ratio of IF bandwidth to baseband bandwidth is given by Downing 6/ as (paragraph 6.3.3.2) as follows:

(12) $$(C/N)_{IF} = 5 + 5 \log_{10} \left(\frac{B_{IF}}{B_m}\right) \quad \text{(@ threshold)}$$

where B_{IF} = IF bandwidth

B_m = signal (baseband) bandwidth

If we assume Carson's Rule for determining the IF bandwidth, we have:

(13) $$B_{IF} \simeq 2\, B_m\, (\beta+1) \quad \text{(neglecting carrier instability)}$$

Therefore (12) becomes

(14) $$(C/N)_{IF} \simeq \left[5 + 5 \log_{10} 2\, (\beta+1)\right] \quad \text{(dB)}$$

$$= \sqrt{20(\beta+1)} \quad \text{(numeric ratio)}$$

Knowing β the required $(C/N)_{IF}$ at threshold can be determined from (14). However, β is determined by the required $(S/N)_o$ at the receiver output. The relation between $(S/N)_o$ and (C/N) above threshold is given by the FM improvement factor:

(15) $$(S/N)_o = 3\beta^2 \left(\frac{BIF}{2B_m}\right) \left(C/N\right)_{IF} \quad \text{(numeric ratio)}$$

$$= 3\beta^2\, (\beta+1)\, (C/N) \quad \text{(using Carson's rule)}$$

$$= 3\beta^2\, (\beta+1) \sqrt{20(\beta+1)} \quad \text{(from 14)}$$

6/ "Modulation Systems and Noise" by J.J. Downing, Prentice-Hall, Inc. Englewood Cliffs, N. J.

Since $(S/N)_o$ is given as 32 dB, the required β may be determined from 15. Since this is a non-linear relation between β and $(S/N)_o$, values for β may be assumed and the $(S/N)_o$ computed from 15. For $\beta = 3$, $(S/N)_o$ is 29.8 dB. For $\beta = 4$, $(S/N)_o$ is 33.8 dB. Therefore, a β of 4 will be assumed and from 14:

(16) $$(C/N) \approx 5 + 5 \log_{10}(10)$$

$$10 \text{ dB} \qquad (\beta = 4)$$

6.3.3.3 Spectrum Utilization. Again assuming that Carson's Rule applies, and neglecting carrier instability which would be applicable to modulation, we have:

(17) $$B_{IP} = 2f_m\ (\beta+1)$$

$$= 2\text{x}2000(4+1)$$

$$= 20 \text{ kHz}$$

6.3.3.4 Equipment Complexity. From the standpoint of hardware requirements, linear FM provides the simplest and least complex system. However, it is able to do this at the expense of requiring a real time repeater and separate input/output channels. The duplexer required in the repeaters would probably require more space than the digital storage required in DM and PCM. The electronic circuitry required in sensors and receivers would be considerably less complex than for DM and PCM and since the majority of equipment elements are sensors, the overall impact on hardware would favor linear FM as a transmission method for analog data.

6.3.3.5 Relative Costs. As compared to DM the added cost of linear FM for sensors and receivers would be at least 30% less. For repeaters the differential would not be so great due to the cost of the duplexer required for the analog system to operate in real time or separate input/output frequencies. The net difference in costs would depend upon the relative quantities of repeaters, and sensors used but it is expected that a 20% difference in favor of linear FM would result. As compared to PCM, the differential in cost for sensors and receivers would range from 75 to 100% in favor of linear FM. Due to lesser digital storage required for PCM vice DM the difference in cost for repeaters would be less for PCM than for DM, however the net difference would be at 60 to 80% in favor of linear FM.

TABLE IX - I

RELATIVE VALUES FOR ALTERNATIVE CRITERIA

ALTERNATIVES	CRITERIA: SIGNAL QUALITY	POWER REQUIREMENTS TO OBTAIN FM THRESHOLD	SPECTRUM UTILIZATION (CHANNEL BANDWIDTH)	EQUIPMENT COMPLEXITY	EQUIPMENT COSTS	
A. DIGITAL: DELTA MODULATION	GOOD	9.3 dB	80 kHz	MODERATE	MEDIUM	
B. DIGITAL: PCM	GOOD	10.2 dB	16 kHz	HIGH	MEDIUM/ HIGH	
C. LINEAR FM	FAIR/GOOD	10 dB	20 kHz	LEAST	LEAST	

TABLE IX - II

RELATIVE RATING OF ALTERNATIVES

C R I T E R I A

ALTERNATIVES	SIGNAL QUALITY	POWER REQUIREMENTS	SPECTRUM UTILIZATION	EQUIPMENT COMPLEXITY	EQUIPMENT COSTS	RELATIVE RATING
A. DIGITAL; DELTA MODULATION	10	10	2	6	6	
B. DIGITAL; PCM	10	9.1	10	4	6/4	
C. LINEAR FM	.5/10	9.3	8	10	10	

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III, paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal, maximum, and minimum values of the weighting factors used are given in Table IX-III.

Table IX-IV lists the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion. The evaluation scores in this table are accurate to two significant figures. The last line is the evaluation rating or weighted score for each alternative.

This initial analysis results in the following preference listing of the alternatives.

RANK	ALTERNATIVE	EVALUATION RATING
1	LINEAR FM (C)	8.89
2	DIGITAL; PCM (B)	7.78
3	DIGITAL; DM	6.84

Since the least accurate figures in the calculation are accurate to two significant figures, the evaluation rating given here is accurate to two significant figures.

7.2 Secondary Ranking Techniques. The procedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section are applicable.

The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Table IX-V.

7.3 Comparison of Results - Nominal Values. From Table IX-V the Linear FM (C), Digital PCM (B), and Digital DM (A) alternatives clearly ranked first, second, and third, respectively, since their rank order remained constant throughout while emphasis on high or low scores was performed.

The results are attributable directly to the fact that Alternative C achieved high evaluation scores in all criteria categories while the other alternatives achieved significantly low scores in some of the criteria categories. For example, while all three alternatives achieved two scores of 10, C did not receive any score below 7.5 while B received a 4 and 5 and A received a 2, 6 and 6.

TABLE IX - III
WEIGHTING FACTORS

CRITERION	NOMINAL	MINIMUM	MAXIMUM
SIGNAL QUALITY	.2200	.1300	.2800
POWER REQUIREMENTS	.2000	.1500	.2400
SPECTRUM UTILIZATION	.2100	.1500	.2700
EQUIPMENT COMPLEXITY	.1900	.1400	.2400
EQUIPMENT COSTS	.1800	.1300	.2300

TABLE IX - IV
EVALUATION SCORES

CRITERION	ALTERNATIVES		
	DIGITAL; DELTA MODULATION (A)	DIGITAL; PCM (B)	LINEAR FM (C)
SIGNAL QUALITY (.2200)	10	10	7.5
POWER REQUIREMENTS (.2000)	10	9.1	9.3
SPECTRUM UTILIZATION (.2100)	2	10	8
EQUIPMENT COMPLEXITY (.1900)	6	4	10
EQUIPMENT COSTS (.1800)	6	5	10
EVALUATION RATING	6.84	7.78	8.89

TABLE IX - V

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS AND DIFFERENT WEIGHTING TECHNIQUES

ALTER-NATIVE	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
A	6.64	3	7.49	3	5.90	3	8.83	3
B	7.78	2	8.19	2	7.28	2	9.13	2
C	8.89	1	8.95	1	8.85	1	9.23	1

ALTERNATIVE KEY

A- DIGITAL; DELTA MODULATION
B- DIGITAL; PCM
C- LINEAR FM

8.0 SENSITIVITY ANALYSIS

The procedures and discussions presented in Section III, Paragraph 8.0 apply equally to this section except that the basic data presented in this section are applicable.

8.1 Sensitivity Study Using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 14 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 7 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately.

The results of the additive weighting sensitivity study are plotted in Figure 9-10. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. An examination of Figure 9-10 reveals that the three alternatives retain their rank throughout the sensitivity study and their rank is very stable.

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 44 sensitivity runs were made for the analysis. These runs showed that preference rankings for the alternatives remained extremely stable. Tables IX-VI through IX-X show the resultant final scores and rank order of the alternatives as the indicated major criteria factor weights were varied, for the four analysis techniques.

The alternatives are identified as follows:

RELATIVE TABLE CODE	ALTERNATIVE
A	DIGITAL: DELTA MODULATION
B	DIGITAL: PCM
C	LINEAR FM

The relationship among the evaluation scores for each alternative, the nominal weighting factors for the subcriteria and for the major criteria is as shown in Table IX-IV. Table IX-III additionally includes the maximum and minimum values for the major criteria.

When the five groupings were compared for all techniques, Alternative C received forty first place rankings to four first place rankings for B. In addition, C generally maintained a significantly greater ER value than B whereas in those cases where B outranked C, the ER margin was insignificant. Alternative A was consistantly last by a large ER margin, although the Logarithmic Technique was the most favorable for A and tended to decrease the ER margin with B.

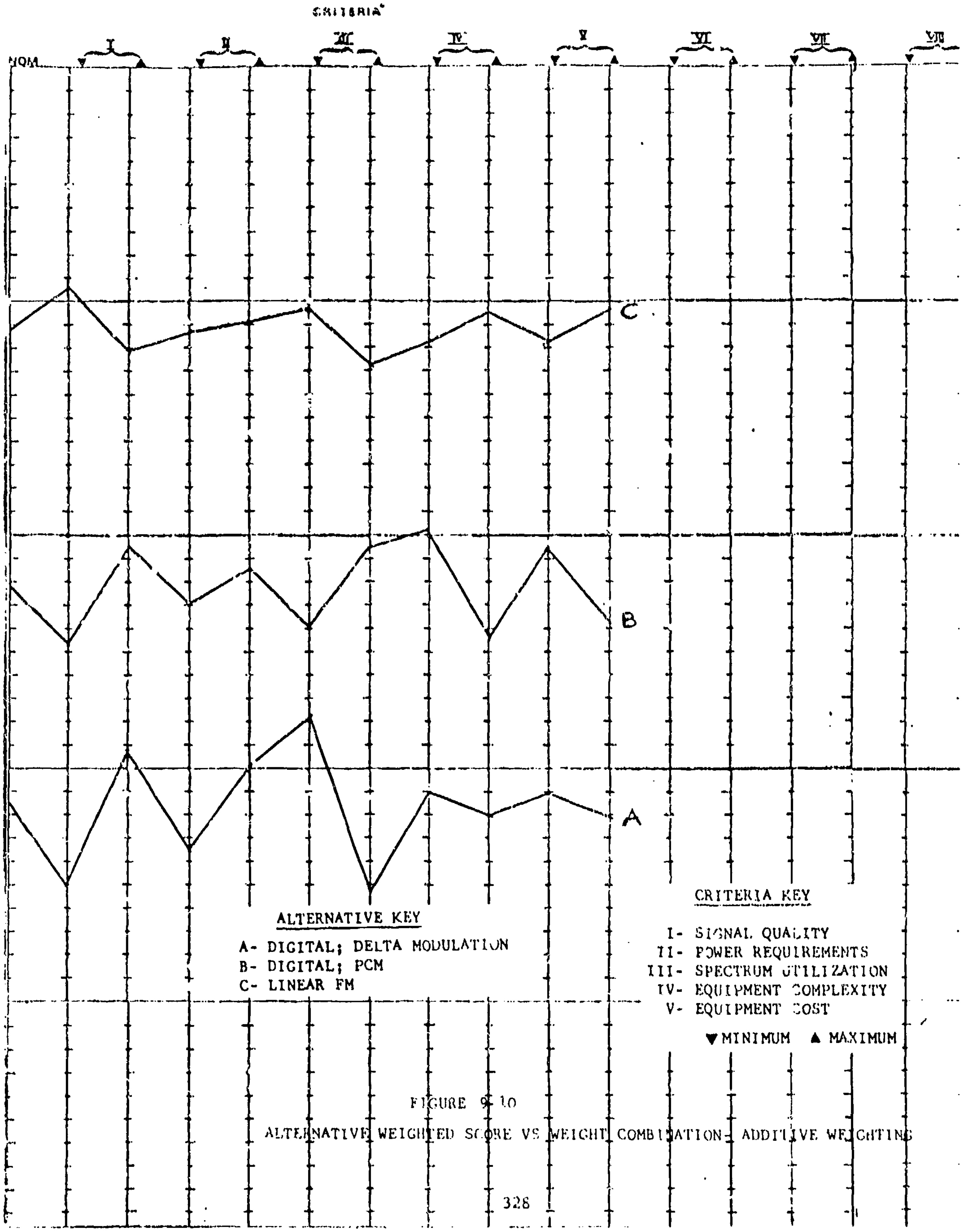


FIGURE 9-10

ALTERNATIVE WEIGHTED SCORE VS WEIGHT COMBINATION - ADDITIVE WEIGHTING

TABLE IX - VI

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING SIGNAL QUALITY FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	6.48	3	7.15	3	5.56	3	8.60	3
B	7.52	2	7.86	2	7.02	2	8.98	2
C	9.05	1	9.10	1	9.00	1	9.34	1
MAX								
A	7.08	3	7.72	3	6.15	3	8.96	3
B	7.95	2	8.54	2	7.46	2	9.22	1
C	8.78	1	8.85	1	8.72	1	9.15	2

WEIGHTS USED IN THESE RUNS

MIN I = .1300, = .2231, = .2345, = .2119,
COST = .2008,

MAX I = .2800, = .1846, = .1938, = .1754,
COST = .1682,

ALTERNATIVE KEY

A- DIGITAL; DELTA MODULATION
B- DIGITAL; PCM
C- LINEAR FM

TABLE IX-VII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING POWER REQUIREMENTS FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	6.64	3	7.31	3	5.71	3	8.71	3
B	7.70	2	8.13	2	7.18	2	9.13	2
C	8.86	1	8.93	1	8.80	1	9.22	1
MAX								
A	7.00	3	7.64	3	6.08	3	8.92	3
B	7.85	2	8.24	2	7.36	2	9.13	2
C	8.91	1	8.97	1	8.85	1	9.23	1

WEIGHTS USED IN THESE RUNS

MIN. 1 = .2337, = .1500, = .2231, = .2019,
COST = .1912,

MAX. 1. = .2090, = .2400, = .1995, = .1805,
COST = .1710,

ALTERNATIVE KEY

A- DIGITAL; DELTA MODULATION
B- DIGITAL; PCM
C- LINEAR FM

TABLE IX - VIII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING SPECTRUM UTILIZATION FACTOR

ALTER- NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	7.21	3	7.75	3	6.41	3	8.93	3
B	7.61	2	8.04	2	7.10	2	9.03	2
C	8.96	1	9.02	1	8.89	1	9.29	1
MAX								
A	6.47	3	7.22	3	5.44	3	8.72	3
B	7.95	2	8.34	2	7.46	2	9.21	1
C	8.82	1	8.88	1	8.76	1	9.16	2

WEIGHTS USED IN THESE RUNS

MIN ; = .2367; = .2152; = .1500; = .2044;
COST = .1937;

MAX ; = .2033; = .1848; = .2700; = .1756;
COST = .1663;

ALTERNATIVE KEY

A- DIGITAL; DELTA MODULATION
B- DIGITAL; PCM
C- LINEAR FM

TABLE IX - IX

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING EQUIPMENT COMPLEXITY FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN								
A	6.89	3	7.58	3	5.90	3	8.90	3
B	8.01	2	8.58	2	7.55	2	9.21	1
C	8.82	1	8.88	1	8.76	1	9.16	2
MAX								
A	6.79	3	7.41	3	5.91	3	8.75	3
B	7.55	2	8.00	2	7.01	2	9.04	2
C	8.96	1	9.02	1	8.90	1	9.29	1

WEIGHTS USED IN THESE RUNS

MIN :	= .2336;	= .2123;	= .2230;	= .1400;
COST = .1911;				
MAX :	= .2064;	= .1877;	= .1970;	= .2400;
COST = .1689;				

ALTERNATIVE KEY

A- DIGITAL; DELTA MODULATION
B- DIGITAL; PCM
C- LINEAR FM

TABLE IX - X

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING EQUIPMENT COST FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN COST								
A	6.89	3	7.58	3	5.90	3	8.90	3
B	7.95	2	8.35	2	7.45	2	9.21	1
C	8.82	1	8.88	1	8.76	1	9.16	2
MAX COST								
A	6.79	3	7.41	3	5.91	3	8.75	3
B	7.81	2	8.03	2	7.31	2	9.04	2
C	8.96	1	9.02	1	8.90	1	9.29	1

WEIGHTS USED IN THESE RUNS

MIN COST: COST = .1300,	= .2334,	= .2122,	= .2228,	= .2016,
MAX COST: COST = .2300,	= .2066,	= .1878,	= .1972,	= .1784,

ALTERNATIVE KEY

A- DIGITAL; DELTA MODULATION
B- DIGITAL; PCM
C- LINEAR FM

9.0 CONCLUSION

The analysis indicates that, if both digital and analog data are to be transmitted in REMBASS, analog data should not be digitized before transmission, but should be used directly as a modulating signal.

10.0 RECOMMENDATION

If both analog and digital data is to be transmitted, analog data should be used directly to modulate the carrier, whereas, the digital data would use dual FM for the two binary states of the digital data.

SECTION X

ENGINEERING ANALYSIS 9
FREQUENCY CHANGING METHODS

1.0 SUMMARY

This analysis addresses the method of frequency changing that should be utilized in the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated by a specific set of criteria; cost, performance, versatility, schedule, technical risk, physical characteristics and human factors. The analysis concluded that three methods of frequency selection should be employed in REMBASS:

1) Digital Frequency Synthesizer

2) Single Frequency Oscillator Module

3) Crystal Substitution

These methods are to be utilized selectively on certain DTS equipments.

2.0 INTRODUCTION

The REMBASS system is composed of several major subsystems. Several different alternative subsystem designs may be found which provide the system operational and functional requirements of REMBASS within certain constraints. In order to determine which subsystem alternative provides the best choice, alternatives are evaluated and analyzed against common criteria and one or more possible alternatives are selected as candidates for final system components.

This analysis is concerned with the selection of a means for setting or selecting the frequencies to be used in the REMBASS DTS equipment.

3.0 STATEMENT OF THE PROBLEM

The employment of large numbers of sensors and repeaters in a division or larger unit operation requires the assignment of many transmitter and receiver frequencies.

Flexibility in and ease of selection of channels is essential to effective utilization of Commandable and Non-Commandable Sensors, Sensor Control Modules (SCM), Repeaters, and Universal Control Receiver/Transmitters UCR/T. Five possible alternatives for channel selection are considered herein.

4.0 ALTERNATIVES

Methods of changing RF operating channels in sensors, repeaters, receivers, etc. will be evaluated against common criteria. These alternatives are defined and described below.

4.1 Digital Frequency Synthesizer (Alternative 1). A device which is designed to permit selection of any one of a discrete set of radio frequencies, easily and arbitrarily, by a switch action or similar means. These frequencies may be used as a local oscillator in a multi-channel receiver or as a carrier source in a transmitter. When used in a transmitter the synthesizer may contain the necessary modulation circuitry in addition to the frequency generation and selection circuitry. In the application envisioned here, the output frequency is assumed to be the desired carrier frequency without a requirement for additional frequency conversion circuitry. A block diagram of a typical synthesizer is shown in Figure 10-1. As can be seen from the block diagram, this alternative essentially includes some of the other alternatives as well as much of the ingredients of a low power modular transmitter such as would be used in sensors, repeaters, or command transmitters. This fact will have to be considered when comparing the various alternatives against the criteria used in the evaluation and ratings.

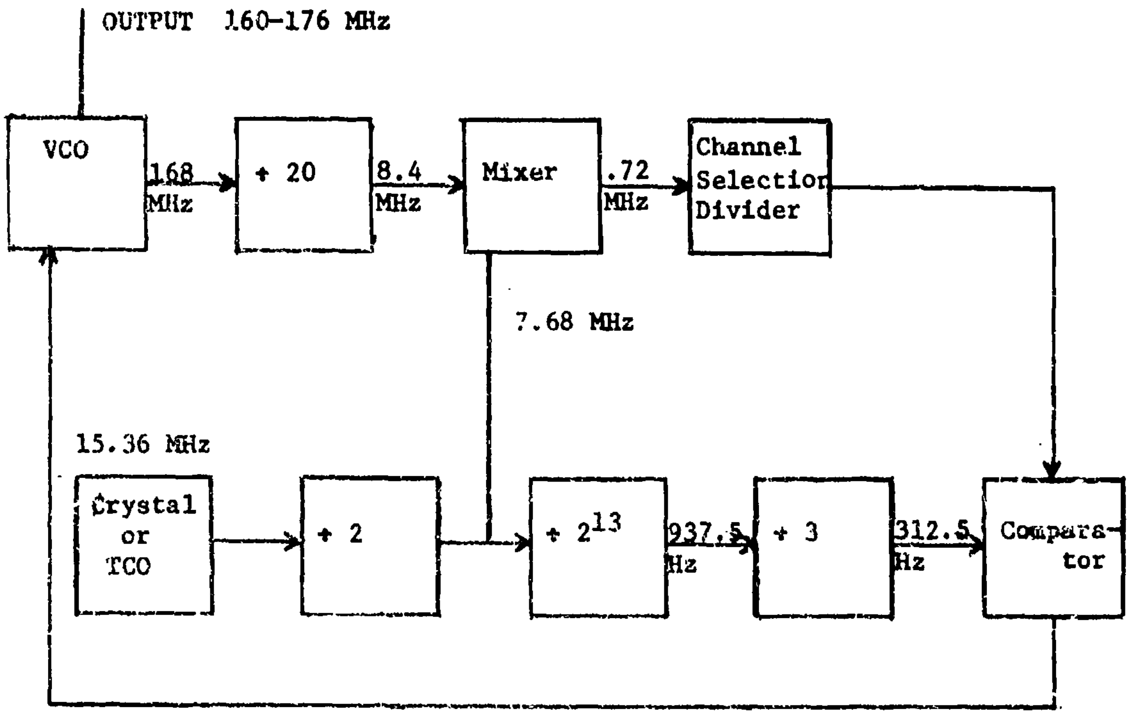


FIGURE 10-1

SIMPLE SYNTHESIZER

4.2 Single Frequency Oscillator Module (Alternative 2). This alternative is a method of achieving higher frequency stability in a receiver, in the RF output of a transmitter, or in the reference frequency for a synthesizer over a wider range of operating temperatures through the incorporation of a temperature compensation network and a crystal. The network is tailored during manufacture to a desired precision of match of the temperature/frequency characteristic of the crystal. A separate module is required for each receiver or transmitter channel. As noted earlier one Temperature Compensated Crystal Oscillator (TCXO)/Temperature Compensated Voltage Controlled Crystal Oscillator (TCVCXO) is a necessary part of a high stability synthesizer. When such a module is used in a receiver frequency, it is referred to as a TCXO. When the module incorporates additional circuitry for modulating the RF output of the transmitter it is referred to as a TCVCXO.

4.3 Crystal Substitution (Alternative 3). This alternative is a means of selecting a DTS RF channel merely by crystal substitution in the reference local oscillator of the transmitter or receiver equipment. After the crystal substitution a "tweaking" adjustment may be required on the local oscillator to bring the frequency within the specified tolerance for the selected channel. As with the modular oscillator alternative, a separate item (crystal) is required for each channel used by a transmitter or receiver.

4.4 Combination of Above Alternatives (Alternative 4). Since there are advantages and disadvantages to the above alternatives depending upon the application, this alternative considers the merits of using more than one of the above to provide the frequency selection capability.

4.5 End Item With Factory Set Frequency Using Option 4.3. In this alternative, the frequency of an end item transmitter or receiver is set at the time of manufacture and is not subject to change in the field. This alternative requires prediction of operating channels but eliminates the stocking of additional components, as well as frequency adjustment required by alternative 3.

5.0 CRITERIA

Criteria used in the comparative evaluation of the alternatives of this engineering analysis are defined below. In paragraph 6.0 each alternative is evaluated against these criteria. In performing the final evaluation each criterion is weighted in proportion to its importance as determined from Material Need (MN) requirements or other pertinent facts. In cases where the relative weight of a criterion is not considered exact, a sensitivity analysis will be performed to determine the effects of errors in the weighting factor.

5.1 Cost. This criterion includes all costs of: a) research and engineering development; b) initial purchase and supply of each designated army element with the required items; and c) the continuing resupply of the frequency setting components of the alternatives, and the supporting costs for the expected life cycle of the system.

5.1.1 R&D Costs. This is the cost required to develop and test the alternative to the point where production can begin.

5.1.2 Acquisition Costs. This is the cost involved in procuring the initial quantity of transmitter and receiver items employing the alternatives to equip army units slated to carry REMBASS items on their Table of Equipment allowances, and provide the frequency selection capability required.

5.1.3 Life Cycle Support Costs. These are the costs of replenishment of items consumed, costs of crew or support personnel, costs of inventory management, transportation, depot maintenance, and test equipment of the frequency setting alternatives.

5.2 Performance.

5.2.1 Stability. This criterion relates to the precision with which an alternative can maintain frequency stability.

5.2.2 Power. This criterion relates to the power consumed by the alternatives.

5.2.3 Reliability. This is the probability that the alternatives can provide the frequency stability required, over the required operating conditions, for the expected operating time of the end items.

5.3 Versatility. This criterion relates to the number of instances or system applications an alternative can satisfy. It also considers the degree to which alternatives can affect DTS design to reduce end item or overall system costs such as thru shared use of the frequency setting means by associated receivers and transmitters or the elimination of duplicate end items, as in repeaters, where operation on either of two channels may be required.

5.4 Development Schedule. This criterion relates to the time yet required to complete research and development of alternatives and prepare for large scale production.

5.5 Development Risk. This criterion considers the magnitude of the technical barriers that must be overcome in alternatives and the probability of doing this within the development schedule.

5.6 Physical Characteristics.

5.6.1 Size. The area of volume demands of an alternative.

5.6.2 Weight. The weight impact of alternatives.

5.7 Human Factors. The ease and flexibility of using each alternative in different applications in the REMBASS DTS.

6.0 EVALUATION OF ALTERNATIVES

6.1 General. The optimum alternative for setting transmit and receive channels may differ with application (i.e. in sensors, SCM repeaters and in UCR/T) because of the different functions that must be performed in the application or because of power, space, or cost constraints. Special features of each application that impact greatly on the channel selection methods are discussed below.

6.1.1 Non-Commandable Sensor Applications. Because of the large population of non-commandable sensors, overall cost of providing the channel selection capability is a major factor in selecting an alternative for this application. The synthesizer, while the most expensive alternative, provides the full gamet of channel selection; whereas the other alternatives require a separate substitution item for each channel.

6.1.2 Commandable Sensor and SCM Applications. Commandable sensors and SCMs require receivers to detect commands. The duty cycle of a receiver normally approaches 100%. A 330 milliwatt synthesizer that would be satisfactory for a sensor transmitter with a less than 1% duty cycle, may not be acceptable in the receiver of a commandable sensor, particularly those deployed in areas which do not permit battery replacement or where replacement poses a great risk to personnel. Even an 80 milliwatt TCXO of alternative 2 has about twice the power drain of the SEAOPSS Phase III receiver, and may not be acceptable. It is possible that considerable relief in the power drain problem of a synthesizer or TCXO controlled receiver can be obtained through a reduction of its duty cycle to about 10%, with a 1 second "ON" period and repetitive transmission of commands until a sensor response message is received. Commandable sensors also require a receiver and decoder and therefore are considerably higher in cost than non-commandable sensors however, their number will be considerable less. Reduction in cost of the receiver may be achieved through a time shared use of a synthesizer of the associated transmitter.

6.1.3 Repeaters. Repeaters will be relatively few in number. They must receive on one channel and may have to retransmit on either of two selected channels. The receiver must be "ON" continuously except while the repeater is retransmitting. The possible need to switch between 2 selected transmit frequencies suggests use of a synthesizer which can switch from one channel to another in about 35 milliseconds.

Because of the 100% receiver duty cycle the size limitations on the repeater package or mission time may have to be relaxed to permit synthesizer or TCXO operation.

6.1.4 UCR/T. The function of the UCR/T is to transmit commands to sensors receiving on particular channels and to receive response messages from sensors sent on other channels. A frequency synthesizer in this application is a practical necessity because of the need to change channels frequently. There are no constraints in power, space, or cost for this application so the synthesizer is the probable logical choice.

6.2 Costs.

6.2.1 R&D Costs (see Table X-I). Further development and production engineering effort for the TCXO/TCVCXO R&D effort for a lower power synthesizer may be required to permit its use in receiver applications, particularly repeaters, unless constraints on battery size, weight, or mission time are eased. Pursuing R&D for Higher Stability does not appear promising.

TABLE X-I

R&D COSTS OF ALTERNATIVES

ALTERNATE	REMARKS	RATING
1	Highest R&D cost	4
2	Lesser cost than (1)	6
3	None	10
4	Intermediate to alternatives	7
5	None	10

6.2.2 Acquisition Cost. Evaluation of the alternatives based on the cost of the frequency setting alternative alone is a misleading method of comparison. Alternative 1 provides a complete channel selection capability but it is necessarily higher in cost than alternatives 2 and 3 which provide just a single channel capability and require substitution of different parts for setting each disired channel. For this reason, it is considered more meaningful to follow the definition of acquisition cost given in paragraph 5.1.2 and consider the cost of the alternatives in terms of providing a required channel selection capability in receivers and transmitters. Insight into the relative cost of these alternatives in providing the frequency selection capability is obtained by considering the relative cost of end items and the required substitution parts. If REMBASS transmitter is a conventional digital-analog transmitter of SEAOPSS Phase III type, the crystal (alternative 3) will account for about 8% of the end item cost (and a lesser percentage of receiver cost). If a TCVCXO were used in a transmitter instead of the crystal it would account for an estimated 40% of the cost of the transmitter. A synthesizer in addition to requiring a TCVCXO for the reference frequency, would require about 30% more electronic components and the cost of these components would increase the cost of the transmitter (apart from TCVCXO) by 30%. The cost of a complete synthesizer transmitter with TCVCXO would be about 1.7 times as much as a transmitter using alternative 3. However, since additional crystals would be required for the latter to provide the required channels, the cost differential of alternative 1 will be reduced as the number of channels increases. The cost of alternative 1 will be less for more than 9 channels. If the crystal does not provide adequate stability for the REMBASS DTS, the TCVCXO (alternative 2) must be the basis for cost comparison. The cost of the synthesizer alternative will be less if more than 2 channels is required. In view of indications that REMBASS will have more than 100 channels, the relative cost of providing this channel selection capability is shown in Table X-II. If alternative 3 is unacceptable for the REMBASS DTS, the ratings reflected in Table X-II will hold for a system of more than 2 channels. Alternative 3, being unacceptable, will be rated "0".

TABLE X-II

RELATIVE ACQUISITION COST OF ALTERNATIVES
TO PROVIDE MORE THAN 9 CHANNEL SELECTION CAPABILITY

ALTERNATIVE	REMARKS	RATING
1	Least Costly	10
2	High Cost	2
3	Lesser cost than 2 (if adequate in stability)	5/0
4	Intermediate to 1 and 2 or 3	6/7
5	Most Costly (end item replacement)	1

6.2.3 Life Cycle Support Costs.

6.2.3.1 Consumption (see Table X-III).

TABLE X-III

RELATIVE COST OF CONSUMED ITEM REPLENISHMENT

ALTERNATIVE	REMARKS	RATING
1	Unit cost being high, replacement cost is high	3
2	Unit cost higher than 3; but one item is required per channel	5
3	Least unit cost; but requires one item per channel	10
4	Intermediate to 1 & 2 or 1 & 3	4/6
5	End item must be replaced - highest cost	1

6.2.3.2 Crew and Personnel. The training and skill level of personnel to service all alternatives does not differ significantly.

6.2.3.3 Test Equipment. Test equipment requirements do not differ significantly for the alternatives.

6.2.3.4 Integrated Logistics Management (See Table X-IV).

TABLE X-IV

RELATIVE COSTS OF LOGISTICS MANAGEMENT OF ALTERNATIVES

ALTERNATIVE	REMARKS	RATING
1	Only one item to manage - least cost	10
2	One item per channel to manage	3
3	One item per channel to manage	3
4	One more item to manage than alternatives 2 or 3	2
5	One end item per channel to manage also requires long range forecast of requirements	1

6.2.3.5 Transportation (see Table X-V).

TABLE X-V

RELATIVE COST OF TRANSPORTATION OF ALTERNATIVES

ALTERNATIVE	REMARKS	RATING
1	End item must be shipped (1 lb)	5
2	Least demands (1 ounce item)	10
3	Least demands (1 ounce item)	10
4	Intermediate 1 & 2 or 3	8
5	End items must be shipped (1 lb)	5

6.3 Performance.

6.3.1 Stability (see Table X-VI). The stability of alternative 1 is set by the stability of the TCXO of the synthesizer. If modulation is applied to the VCO of the synthesizer rather than the TCXO, this alternative will provide the most stable transmitter carrier frequency. The stability of alternative 2 is not expected to be as good as alternative 1 due to the application of modulation to the TCVCXO, assuming an FM system is used in REMBASS. Alternative 3 has the least stability due to the inability to provide optimum compensation for each crystal. Alternative 4 should be equal to 1 if the synthesizer is used in all transmitters and the TCXO module is used in receivers. Alternative 5 should have a stability comparable to 2, since the compensation could be optimized at the factory for each crystal in fixed tuned oscillators.

TABLE X-VI

COMPARISON OF STABILITY OF ALTERNATIVES

ALTERNATIVE	REMARKS	RATING
1	Best Stability	10
2	Not as good as 1	7
3	Probably unsatisfactory	0
4	Same as 1	10
5	Same as 2	7

6.3.2 Power (see Table X-VII). The importance of the power criterion differs greatly in transmitters and receivers because of their widely different duty cycles. Evaluation of the alternatives on this criterion is most meaningful when done on an end item basis. A 330 milliwatt synthesizer in a 4 watt RF output transmitter imposes a 2-3% increase in primary power over the conventional crystal controlled transmitter. This increase is not too significant for the low duty cycle (1%) of the transmitter. A receiver with a 330 milliwatt synthesizer, is about 8 times greater in power drain than the total power requirement of a SEAOPSS Phase III receiver. Considering that the receiver has a much higher duty cycle, use of a synthesizer as a channel setting means in a receiver may not be acceptable because of the limited energy in the battery pack. The power requirements of other alternatives would be considerably less than for the synthesizer.

TABLE X-VII

POWER RATINGS OF ALTERNATIVES IN END ITEMS

ALTERNATIVE	REMARKS	END ITEM RATING
1	1/4 watt is tolerable for transmitters - may be excessive for receivers	8 trans. receiver 4
2	tolerable in transmitters higher than (3); may be unacceptable in receivers	9 6
3	Least power requirements	10 10
4	Alternative 1 for Tx Alternative 2 for Rx	9 7
5	Least power	10 10

6.3.3 <u>Reliability (see Table X-VIII).</u> In general, reliability decreases with increasing number of parts. Hybrid modules however, tend to improve reliability over discrete components.

TABLE X-VIII

COMPARISON OF RELIABILITY OF ALTERNATIVES

ALTERNATIVE	REMARKS	RATING
1	Most parts - lowest reliability	6
2	Fewer parts	8
3	Fewest parts, but adjustments	8
4	Intermediate to 1 & 2	8
5	Fewest parts, no adjustments	10

6.4 <u>Versatility (see Table X-IX).</u>

6.4.1 <u>Alternative 1</u>. A common synthesizer design can be used in all sensors except the mini-sensors used with an SCM. It may be used in SCM, repeaters, and UCR/T. It may also be used in a UCR where adequate commercial power is available and the flexibility of RF channel selection is a necessity. Since each commandable sensor has both a receiver and transmitter it may be possible to save the cost of a separate synthesizer in the receiver through shared use of the transmitter synthesizer.

In repeaters which retransmit on either of 2 frequencies depending on whether a message is coming from or going to a sensor, the synthesizer affords a facile logic controlled means to switch on the proper transmit channel and obviates need for a second transmitter.

6.4.2 <u>Alternative 2</u>. A TCXO can be used to set a channel in all conventional receivers, and a TCVCXO can be used in all transmitters to set a channel. A different TCVCXO is required for each channel. The alternative is seriously limited in use, due to its being fix tuned to a specific frequency. There is no such constraint when used in synthesizers.

6.4.3 <u>Alternative 3</u>. The same comments as for alternative 2 apply.

6.4.4 <u>Alternative 4</u>. The same comments as for alternatives 1 and 2 and 3 apply.

6.4.5 <u>Alternative 5</u>. Requires separate end item (i.e. transmitter, receiver) for each channel and is least versatile.

TABLE X-IX

VERSATILITY RATING OF ALTERNATIVES

ALTERNATIVE	REMARKS	RATING
1	(Satisfies transmitter applications but has limited use in receivers) Has no TCXO or TCVCXO or crystal substitution problem.	9
2	Satisfies all applications but a module is required for each operating channel.	4
3	May satisfy all applications, but a crystal is required for each operating channel.	4
4	(Most versatile) since it has best features of 1 and 2	10
5	Requires different end item for each channel.	2

6.5 Development Schedule (from July 74) (see Table X-X).

TABLE X-X

DEVELOPMENT SCHEDULE OF ALTERNATIVES

ALTERNATIVE	REMARKS	RATING
1	Depends on stability requirements - 1-2 years	7
2	Depends on stability requirements - 1-2 years	7
3	No improvement seen as possible/25 ppm available	0/10
4	1 - 2 years	7
5	Same as for 3	0/10

6.6 Development Risk (see Table X-XI). A breadboard synthesizer with 250 milliwatt power requirement has been designed and tested in COM/ADP Laboratory. It meets REMBASS temperature requirements and its frequency stability is determined by its reference TCXO. A 50 milliwatt synthesizer suitable for receiver use has not yet been designed to REMBASS temperature and shock requirements. It is believed all synthesizers can withstand the shock requirements of REMBASS equipment provided the frequency stability equirement is not too high (±5 ppm limit). The risk associated with alternatives 2 and 3 are heavily dependent on the final frequency stability requirements. It is doubtful that a crystal substitution technique can be developed to meet ± 5ppm stability. It is possible that this can be accomplished with a TCVCXO but as yet, the state of the art is questionable.

TABLE X-XI

DEVELOPMENT RISK FOR ALTERNATIVES

ALTERNATIVE	REMARKS	RATING
1	.25 Watt Synthesizer - small risk .050 Watt (or lower power) Synthesizer (moderate risk)	9 5
2	Medium	8
3	Serious risk for high stability requirements	3/10
4	Medium	8
5	Same as 2	8

6.7 Physical Characteristics (see Table X-XII).

6.7.1 Size. It is deemed feasible to package a discrete synthesizer section (suitable for transmitter use) in a 12 to 16 in^2 PC board area. If this size is excessive, hybridization is expected to reduce size to about 8 in^2, but at an uncertain impact on cost. A hybridized low power synthesizer may be required to satisfy all REMBASS applications.

TABLE X-XII

RELATIVE SIZE OF ALTERNATIVES

ALTERNATIV S	REMARKS	END ITEM RATING
1	PC board area 12 - 16 in^2 (discrete) 6 - 9 in^2 (hybrid)	7 8
2	1-1/4 x 1-1/4 x 1/4" module	9
3	1/2 x 3/8 x 1/4" module	10
4	depends on choice of 1, 2, 3	9
5	depends on choice of 1, 2, 3	9

6.7.2 Weight. Alternatives for setting frequency have weights that do not vary by more than a small fraction of a pound. Impact of end item is insignificant.

6.8 Human Factors (see table X-XIII). Alternative 5 only requires that whoever is assembling a DTS, select the correct channel numbered end item receiver or transmitter and insert it in the proper socket or interface. It presents the least possibility of error and requires minimal skill. Alternative 2 poses an equivalent risk of error and level of skill requirement. Alternative 3 requires additionally, the performance of tuning adjustments by assembly personnel, and therefore poses greater basis for error and requires somewhat greater skill. Alternative 1 requires a working knowledge of decimal to binary code conversion techniques, which may be simplified through use of step-by-step procedures and forms for transcribing the binary code digits of channels from a code table and the setting of binary mini-switches in accordance with the code recorded on the form. This is not a difficult procedure to learn and use, but it poses greater risk of error than other alternatives. This risk can be eliminated by a "buddy" check system. Though somewhat more time consuming, it poses no serious problem in terms of the expected loads or demands for sensor assembly. In the relatively few UCR/T where space, power, and cost pose no problems, automatic code conversion can be provided whereby the operator need only set switches to desired decimal digits. Logic components can automatically output the correct voltage levels to set the synthesizer to correct channels. These digi-switches permit rapid error free change in transmit and receive channels as required in UCR/T operations. The use of a synthesizer greatly simplifies logistics support paper work since only one NSN end item is required rather than a number of NSN end items equal to the channel capacity. This can be the source of error in transcribing and transmission of ordering information. The synthesizer also eliminates the need for long range forecasting, which may be the source of considerable prediction errors.

TABLE X-XIII

HUMAN FACTORS RATING OF ALTERNATIVES

ALTERNATIVE	REMARKS	RATING
1	Has very favorable human factor aspects	10
2	Less chance of error than 3; considerable chance of logistic errors	8
3	Tweeking operating poses source of error; considerable chance of logistic errors	6
4	Depends on alternatives 1 & 2 or 1 & 3; considerable chance of logistic errors	8/7
5	Least chance of error in using; considerable errors in logistics	8

TABLE X - XIV

RELATIVE RATING OF ALTERNATIVES VS. CRITERIA

CRITERIA

	COST			PERFORMANCE						PHYSICAL CHAR.	
ALTERNATIVE	R&D	ACQUISITION	LIFE CYCLE SUPPORT	STABILITY	POWER	RELIABILITY	VERSATILITY	DEVELOPMENT SCHEDULE	DEVELOPMENT RISK	SIZE	HUMAN FACTORS
1	4	10	6	10	6	6	9	7	5/9	7/8	10
2	6	2	6	7	7.5	8	4	7	8	9	8
3	10	5/0	7.7	0	10	8	4	0/10	3/10	10	6
4	7	6/7	5	10	8	8	10	7	8	9	8/7
5	10	1	2.3	7	10	10	2	0/10	8	9	8

TABLE X - XV

LIFE CYCLE SUPPORT COSTS RATING

ALTERNATIVE	CONSUMPTION	CREW & PERSONNEL	TEST EQUIPMENT	ILS	TRANSPORTATION	LCS RATING
	CRITERIA					
1	3	10	10	10	5	6.0
2	5	10	10	3	10	6.0
3	10	10	10	3	10	7.7
4	4/6	10	10	2	8	5.0
5	1	10	10	1	5	2.3

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III, paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal, maximum, and minimum values of the weighting factors used are given in Table X-XVI.

Table X-XVII lists the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion. The evaluation scores in this table are accurate to two significant figures. The last line is the evaluation rating or weighted score for each alternative.

TABLE X-XVI

WEIGHTING FACTORS

		NOMINAL WEIGHT		WEIGHT RANGE	
		MAJOR FACTOR	SUB FACTOR	MINIMUM	MAXIMUM
I	COST	.2000		.1250	.3500
	1 R&D		.2000		
	2 Acquisition		.3875		
	3 Life Cycle Support		.4125		
II	PERFORMANCE	.2750		.2125	.4175
	1 Stability		.2900		
	2 Power		.3150		
	3 Reliability		.3950		
III	VERSATILITY	.1875		.1250	.2750
IV	SCHEDULE	.1000		.0525	.1750
V	TECHNICAL RISK	.0875		.0475	.1550
VI	PHYSICAL	.0875		.0325	.1250
VII	HUMAN FACTORS	.0625		.0350	.1125

TABLE X-XVII

EVALUATION SCORES

	A	B	C	D	E
I COST (.2000)					
1 R&D (.2000)	4.0	8.0	10.0	7.0	10.0
2 Acquisition (.3875)	10.0	2.0	2.5	6.5	1.0
3 Life Cycle Support (.4125)	8.0	6.0	7.7	5.0	2.3
II PERFORMANCE (.2750)					
1 Stability (.2900)	10.0	7.0	[illegible]	10.0	7.0
2 Power (.3150)	6.0	7.5	10.0	8.0	10.0
3 Reliability (.3950)	6.0	8.0	8.0	8.0	10.0
III VERSATILITY (.1875)	9.0	4.0	4.0	10.0	2.0
IV SCHEDULE (.1000)	7.0	7.0	9.0	7.0	5.0
V TECHNICAL RISK (.0875)	7.0	8.0	6.5	8.0	8.0
VI PHYSICAL (.0875)	7.5	9.0	10.0	9.0	9.0
VII HUMAN FACTORS (.0625)	10.0	8.0	6.0	7.5	8.0
EVALUATION RATING	7.68	6.40	6.03	8.09	6.04

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

This initial analysis results in the following preference listing of the alternatives.

RANK	ALTERNATIVE	EVALUATION RATING
1	Combination of Alternatives A,B,C,- (D)	8.09
2	Digital Frequency Synthesizer - (A)	7.68
3	Single Frequency Oscillator Module - (B)	6.40
4	Fixed Frequency/Factory Set - (E)	6.04
5	Crystal Substitution - (C)	6.03

Since the least accurate figures in the calculation are accurate to two significant figures, the evaluation rating given here is accurate to two significant figures.

7.2 Secondary Ranking Techniques. The prodedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section are applicable.

7.3 Comparison of Results - Nominal Values. From Table X-XVIII Alternatives D (a combination of Alternatives A,B,C) and A (Digital Frequency Synthesizer) ranked first and second, respectively, with D clearly above A. This was indicated by the fact that D outranked A for all of the evaluation techniques. Examination of the evaluation scores in Table X-XVII indicated that, based purely on score value alone, D outranked A by only a very small margin. However, when the weighting factors of Table X-XVI were examined in conjunction with the evaluation scores, it was seen that D tended to outscore A in the higher weighted criteria; notably II and III. In opposition, A outranked D in only one highly weighted criterion; I. The remainder of the alternatives were significantly lower in ER value than A and D, but were also rather closely grouped with no stability between the four calculation techniques.

TABLE X-XVIII

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS AND DIFFERENT WEIGHTING TECHNIQUES

ALTERNATIVE	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
A	7.88	2	7.87	2	7.48	2	8.57	2
B	6.40	3	6.71	5	5.97	3	7.33	5
C	6.03	5	6.77	4	5.62	5	8.14	4
D	8.09	1	8.22	1	7.94	1	8.75	1
E	6.04	4	6.92	3	4.76	4	8.40	3

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

8.0 SENSITIVITY ANALYSIS

The procedures and discussions presented in Section III, paragraph 8.0 apply equally to this section except that the basic data presented in this section are applicable.

8.1 Sensitivity Study Using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 14 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 7 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately.

The results of the additive weighting sensitivity study are plotted in Figure 10-2. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. An examination of Figure 10-2 reveals that the top two alternatives D and A, retain their rank throughout the sensitivity study. Their rank is very stable. The outcome for the remainder of the alternatives indicates that B generally ranks third but that C and E are approximately equal in ranking. Alternatives B, C, and E have ER values significantly below those of A and D and tend to form a group by themselves. The results indicated in Figure 10-2 are in agreement with the results of 7.3. The resultant preference grouping derived from Figure 10-2 is listed below:

Group I	Combination of Alternatives A,B,C - (D)
Group II	Digital Frequency Synthesizer - (A)
Group III	Single Frequency Oscillator Module - (B)
	Crystal Substitution - (C)
	Frequency/Factory Set - (E)

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 60 sensitivity runs were made for the analysis. These runs showed that preference rankings for the two leading alternatives. D and A respectively, remained constant while some shifting occured among the remaining alternatives. Tables X-XIX through X-XXV show the resultant final scores and rank order of the alternatives as the indicated major criteria factor weights were varied for the four analysis techniques. The relationship among the evaluation scores for each alternative, the nominal weighting factors for the subcriteria and for the major criteria is as shown in Table X-XVII. Table X-XVI additionally includes the maximum and minimum values for the major criteria. When the seven groupings were compared with the results obtained for RMS, Multiplicative and Logarithmic Weighting Techniques, see Table X-XXVI, Alternative D ranked first in fifty-nine of the sixty runs and B ranked second in fifty-eight of the sixty, thereby clearly confirming the earlier results. For the third ranked alternative, a change was indicated.

Alternatives E and B received twenty-nine and twenty-eight third place rankings, respectively. However, E also received twenty-four fourth place rankings whereas B received only 7. Therefore, based on an average of all sixty runs, E would rank third and B fourth. Alternative C, which had previously ranked near the bottom, is now seen to clearly rank last.

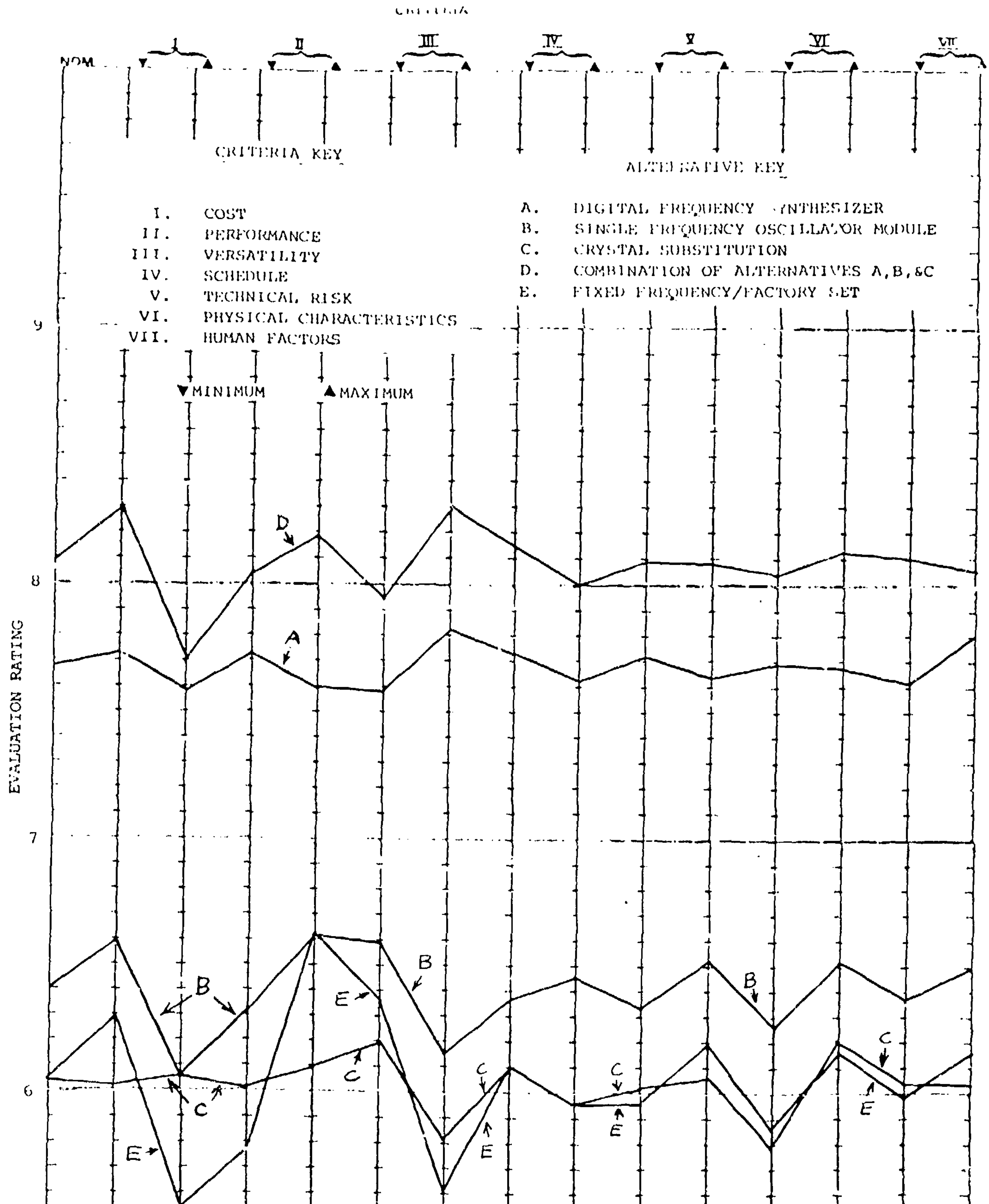


FIGURE 10-2
ALTERNATIVE WEIGHTING VS. WEIGHTING COMBINATION - ADDITIVE WEIGHTING

TABLE X -XIX

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING COST FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN COST								
A	7.73	2	7.90	2	7.55	2	8.55	2
B	6.59	3	6.86	4	6.22	3	7.43	5
C	6.02	5	6.71	5	3.50	5	8.14	4
D	8.28	1	8.40	1	8.16	1	8.86	1
E	6.29	4	7.09	3	5.11	4	8.46	3
MAX COST								
A	7.58	2	7.81	2	7.34	2	8.60	1
B	6.04	4	6.00	5	5.52	3	7.11	5
C	6.05	3	6.75	3	3.88	5	8.15	4
D	7.69	1	7.86	1	7.51	1	8.50	2
E	5.53	5	6.57	4	4.13	4	8.30	3

WEIGHTS USED IN THESE RUNS

MIN COST: COST = .1290; PERF = .3008; VERS = .2051; SCHD = .1094;
RISK = .0957; PHYS = .0957; H F = .0684;

MAX COST: COST = .3500; PERF = .2234; VERS = .1523; SCHD = .0812;
RISK = .0711; PHYS = .0711; H F = .0508;

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

TABLE X-XX

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING PERFORMANCE FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PERF								
A	7.73	2	7.91	2	7.53	2	8.58	2
B	6.31	3	6.63	5	5.86	3	7.30	5
C	6.01	4	6.65	4	3.98	5	8.08	4
D	8.04	1	8.19	1	7.89	1	8.73	1
E	5.77	5	6.68	3	4.51	4	8.24	3
MAX PERF								
A	7.58	2	7.78	2	7.38	2	8.54	3
B	6.62	4	6.88	5	6.24	3	7.39	5
C	6.09	5	6.88	4	2.96	5	8.27	4
D	8.18	1	8.30	1	8.05	1	8.78	1
E	6.63	3	7.01	3	5.37	4	8.71	2

WEIGHTS USED IN THESE RUNS

MIN PERF: COST = .2172; PERF = .2125; VERS = .2037; SC = .1086; RISK = .0950; PHYS = .0950; H F = .0679;

MAX PERF: COST = .1621; PERF = .4125; VERS = .1519; SCHD = .0810; RISK = .0709; PHYS = .0709; H F = .0506;

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A.B,&C
E. FIXED FREQUENCY/FACTORY SET

TABLE X-XXI

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING VERSATILITY FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN VERS								
A	7.56	2	7.77	2	7.37	2	8.53	2
B	6.59	3	6.88	5	5.16	3	7.43	5
C	6.19	5	6.89	4	3.60	5	8.25	4
D	7.94	1	8.[illegible]7	1	7.80	1	8.59	1
E	6.35	4	7.16	3	5.09	4	8.51	3
MAX VERS								
A	7.82	2	8.00	2	7.63	2	8.62	2
B	6.15	3	6.07	5	5.72	3	7.18	5
C	5.81	4	6.48	4	3.66	5	7.99	4
D	8.29	1	8.43	1	8.14	1	8.[illegible]5	1
E	5.61	5	6.57	3	4.34	4	8.24	3

WEIGHTS USED IN THESE RUNS

MIN VERS: COST = .2154; PERF = .2962; VERS = .1250; SCHD = .1077; RISK = .0942; PHYS = .0942; H F = .0573;

MAX VERS: COST = .1785; PERF = .2454; VERS = .2750; SCHD = .0392; RISK = .0781; PHYS = .0781; H F = .0558;

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

TABLE X-XXII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING DEVELOPMENT SCHEDULE FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN SCHD								
A	7.72	2	7.01	2	7.51	2	8.62	2
B	6.37	3	6.70	5	5.92	3	7.35	5
C	6.09	5	6.80	4	3.56	5	8.21	4
D	8.14	1	8.28	1	7.99	1	8.80	1
E	6.10	4	7.01	3	4.75	4	8.47	3
MAX SCHD								
A	7.62	2	7.80	2	7.44	2	8.49	2
B	6.45	3	6.74	4	6.05	3	7.30	5
C	5.95	5	6.60	5	3.72	5	8.03	4
D	8.00	1	8.13	1	7.86	1	8.66	1
E	5.95	4	6.78	3	4.78	4	8.29	3

WEIGHTS USED IN THESE RUNS

MIN SCHD: COST = .2106; PERF = .2895; VERS = .1974; SCHD = .0525;
RISK = .0921; PHYS = .0921; H F = .0658;

MAX SCHD: COST = .1833; PERF = .2521; VERS = .1719; SCHD = .1750;
RISK = .0802; PHYS = .0802; H F = .0573;

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

TABLE X-XXIII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING DEVELOPMENT RISK FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN RISK								
A	7.71	2	7.90	2	7.50	2	8.61	2
B	6.33	3	6.55	5	5.90	3	7.29	5
C	6.01	4	6.73	4	3.53	5	8.19	4
D	8.09	1	8.23	1	7.94	1	8.77	1
E	5.95	5	6.87	3	4.65	4	8.42	3
MAX RISK								
A	7.63	2	7.81	2	7.44	2	8.49	2
B	6.52	3	6.81	4	6.10	3	7.39	5
C	6.07	5	6.71	5	3.78	5	8.07	4
D	8.08	1	8.21	1	7.94	1	8.70	1
E	6.19	4	7.01	3	4.95	4	8.38	3

WEIGHTS USED IN THESE RUNS

MIN RISK: COST = .2088; PERF = .2871; VERS = .1957; SCHD = .1044;
RISK = .0475; PHYS = .0913; H F = .0652;

MAX RISK: COST = .1852; PERF = .2547; VERS = .1736; SCHD = .0926;
RISK = .1550; PHYS = .0810; H F = .0579;

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

TABLE X-XXIV

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING PHYSICAL CHARACTERISTICS FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PHYS								
A	7.69	2	7.89	2	7.48	2	8.61	2
B	7.25	3	6.55	4	5.83	3	7.13	5
C	5.79	5	6.47	5	3.41	5	7.90	4
D	8.03	1	8.17	1	7.88	1	8.73	1
E	5.85	4	6.77	3	4.58	4	8.36	3
MAX PHYS								
A	7.67	2	7.85	2	7.48	2	8.54	2
B	6.51	3	6.82	5	6.08	3	7.45	5
C	6.20	4	6.59	4	3.78	5	8.29	4
D	8.12	1	8.28	1	7.98	1	8.76	1
E	6.16	5	7.02	3	4.89	4	8.43	3

WEIGHTS USED IN THESE RUNS

MIN PHYS: COST = .2121, PERF = .2918, VERS = [illegible], SCHD = .1060,
RISK = .0928, PHYS = .0325, H F = .0663,

MAX PHYS: COST = .1918, PERF = .2637, VERS = .1798, SCHD = .0959,
RISK = .0839, PHYS = .1250, H F = .0599

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

TABLE X-XXV

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING HUMAN FACTORS FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN H F								
A	7.61	2	7.80	2	7.42	2	8.49	2
B	6.36	3	6.67	5	5.92	3	7.30	5
C	6.03	4	6.74	4	3.57	5	8.18	4
D	8.10	1	8.34	1	7.95	1	8.77	1
E	5.98	5	6.89	3	4.69	4	8.41	3
MAX H F								
A	7.80	2	8.00	2	7.60	2	8.69	2
B	6.49	3	6.79	4	6.07	3	7.37	5
C	6.03	5	6.69	5	3.72	5	8.08	4
D	8.06	1	8.19	1	7.91	1	8.70	1
E	6.15	4	6.98	3	4.90	4	8.39	3

WEIGHTS USED IN THESE RUNS

MIN H F : COST = .2059; PERF = .2831; VERS = .1730; SCHD = .1029;
RISK = .0901; PHYS = .0901; H F = .0350;

MAX H F : COST = .1893; PERF = .2603; VERS = .1775; SCHD = .0947;
RISK = .0828; PHYS = .0828; H F = .1125;

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

TABLE X-XXVI

CUMULATIVE RANK FREQUENCY TABLE- ALL METHODS

ALT	MODE	MEAN	1ST	2ND	3RD	4TH	5TH
A	2	2.000	1	58 *	1	0	0
B	3	3.950	0	0	28 *	7	25
C	4	4.450	0	0	2	29 *	29
D	1	1.017	59 *	1	0	0	0
E	3	3.583	0	1	29	24	6

ALTERNATIVE KEY

A. DIGITAL FREQUENCY SYNTHESIZER
B. SINGLE FREQUENCY OSCILLATOR MODULE
C. CRYSTAL SUBSTITUTION
D. COMBINATION OF ALTERNATIVES A,B,&C
E. FIXED FREQUENCY/FACTORY SET

9.0 CONCLUSION

The analysis indicated that three methods of frequency changing should be used in the REMBASS DTS equipment as applicable: a) digital frequency synthesizer; b) single frequency oscillator module; and c) crystal substitution. The former is the more expensive and would only be used in those equipments in which the versatility of frequency selection was an overriding consideration. The second method would be used in equipments in which the need for wide environmental capability (temperature) was required, but frequency changing was seldom required, except at a depot level of maintenance. Crystal substitution only would be used if the accuracy and stability requirements of the equipment was not severe. If $\pm$ 5 ppm frequency stability was required, even at limited temperature ranges, it is not expected that this method would be usable.

10.0 RECOMMENDATIONS

The methods indicated in the analysis and discussed above are recommended.

SECTION XI

ENGINEERING ANALYSIS 10 - MESSAGE CODING

1.0 SUMMARY

This analysis addresses the type of message coding that should be used in the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated against a specific set of criteria, cost and performance. The analysis concluded that a single parity check bit be incorporated in all digital data for error detection.

2.0 INTRODUCTION

This engineering analysis considers possible requirements for coding the digital sensor data for the purpose of detection and/or correction of message error occuring during transmission and reception of sensor messages. In addition, there may be a requirement for securing the data from either reception by an enemy or preventing meaningful information to be obtained from the data if an unfriendly receiver should intercept the message. Generally, the information contained in the sensor messages in not classified. However, unless precautions are taken it is possible for an enemy to intercept messages and use the data to 'spoof' the system in a countermeasure operation.

3.0 STATEMENT OF THE PROBLEM

When digital information is transmitted over an RF channel and decoded after detection by a receiver, there is always a possibility of error in one or more of the received digits due to extraneous factors. There is also the possibility that valid messages are not recognized and therefore missed because of these extraneous factors.

Errors in decoded messages may be due to a variety of causes: a) coincident messages at the receiver from more than one sensor; b) effects of receiver and atmospheric noise which alters the spectral energy content of messages; c) error in message synchronization (or the erroneous identification of the first information digit in a message); and d) deliberate enemy electronic activity calculated to thwart the transfer of sensor information or to produce misleading information (spoofing).

Errors in information digits which are due to external electronic interference or internal receiver noise, may be detected and/or corrected through the addition of check digits to the message. These check digits may be generated in the sensor data encoder in accordance with a rule which permits detection and correction to be performed at the receiver. At the receiver, the message digits and check digits are compared for adherence to the check rule to reveal error in digits which, being identified are then corrected. One of the problems to be addressed by this engineering analysis is whether or not the REMBASS DTS should incorporate this type of coding.

The problem of enemy countermeasures relates to his ability to detect REMBASS messages and using message characteristics to abort the DTS. This engineering analysis also addresses this problem aspect by suggesting coding techniques which may provide some measure of protection against Electronic Countermeasures (ECM).

4.0 ALTERNATIVES

Each of the problems identified in paragraph 3.0 may be investigated, independently and alternative solutions considered against criteria which are applicable to the problem at hand.

4.1 Detection and/or Correction of Message Errors. The alternatives to be compared for this problem area are: a) coding for error detection and correction; b) coding for error detection only; and c) no additional coding for error detection/correction.

4.1.1 Alternative A1; Coding for Error Detection and Correction. In this alternative, redundancy is included in the form of check digits to allow for detection and subsequent correction of random errors. The check digits are set by operating on the data digits in accordance with some mathematical procedure or algorithm. The maximum number of random errors which can be corrected is dependent upon the type of algorithm used.

4.1.2 Alternative B1; Error Detection Only. In this alternative, a single parity check bit is provided to detect an odd number of bit errors in the message. No correction is provided.

4.1.3 Alternative C1; No Coding. In this alternative, no redundancy is provided in the form of extra check bits in the message to detect or correct possible errors in the DTS message. The reliability of the received data is dependent upon the probability of decoding the data correctly.

4.2 Electronic Counter-Countermeasures (ECCM) Coding. The alternatives to be considered for this problem area are: a) secure coding of messages, or pertinent parts of messages, and b) coding to minimize message detection by the enemy.

4.2.1 Alternative A2, Secure Coding. This alternative would provide a message code structure that prevents the enemy from either determining the message data content, or from using the intercepted messages to spoof the REMBASS system operation.

4.2.2 Alternative B2, Camouflage Coding. In this alternative the message is coded in such a manner that minimizes its detection probability by the enemy. An example of this type of coding would be making the message appear to be Gaussian noise.

5.0 CRITERIA

The criteria which will be used in the comparative evaluation of the alternatives are defined below. In paragraph 6.0 each of the alternatives will be analyzed on the basis of these criteria and a relative ranking of the alternatives will be made.

5.1 Costs.

5.1.1 R&D Cost. The alternatives will be compared on the basis of the expected R&D effort required to attain a production posture. This includes necessary modeling, testing, and tooling required for pre-production engineering.

5.1.2 Acquisition Cost. This is the cost required to procure sufficient devices, equipment, etc. for an initial operating capability of the user. The alternatives may be compared on the basis of unit cost if the same number of units are required.

5.1.3 Life Cycle Cost. For these alternatives, the major difference in life cycle support cost is expected to be in the maintenance area. Other life cycle support cost items are not considered of any consequence for these alternatives.

5.2 Performance.

5.2.1 Message Error Rate. Each alternative will be evaluated and ranked according to its expected improvement or impact on the received message error rate. The "no coding" alternative will be the basis for comparing alternatives.

5.2.2 Message Energy Requirements. For remotely located sensors and repeaters, the available battery energy is a critical item in the life of the devices. Therefore, the influence of the alternative on the energy required for each message transmitted is a significant measure of comparison.

5.2.3 Message Self-Interference. Since one or more repeaters will be required on most repeater links, it is imperative that each link handle as many sensors as possible. To minimize the message loss due to interference between independent real time sensor transmissions, the message length should be kept as short as possible. Therefore, the influence on message of each alternative will be evaluated and compared.

5.2.4 ECM/EMI. This criterion measures the relative likelihood of the message either interfering with other collocated data systems, or of being intercepted by an enemy and being used for countermeasure purposes.

5.3 ECCM Coding. The criteria for evaluating the alternatives of this problem area are not synonymous with the previous problem area. The following criteria are considered relevant for the evaluation of the alternatives listed in paragraph 4.2.

5.3.1 Transmission Technique. The various alternatives are not necessarily applicable to any transmission techniques selected for the DTS. For example, an alternative may be dependent upon bandwidth for its efficiency. With regard to the ECCM requirement, it is assumed that the data content of all messages is not classified; therefore, ECCM coding is not for the purpose of depriving the enemy of classified information but rather to prevent his utilizing the messages for countermeasure purposes or to provide information for jamming of the data link.

6.0 TECHNICAL EVALUATION OF ALTERNATIVES

6.1 General. The DTS of REMBASS must provide for the asychronous transmission of data messages from sensors, either direct to a readout unit or via repeaters. The message duty cycle will be very low for a given sensor, although it may be somewhat higher for some repeaters in a given repeater link. The relative duty cycle for a sensor transmission is very short as is indicated in Figure 11-1.

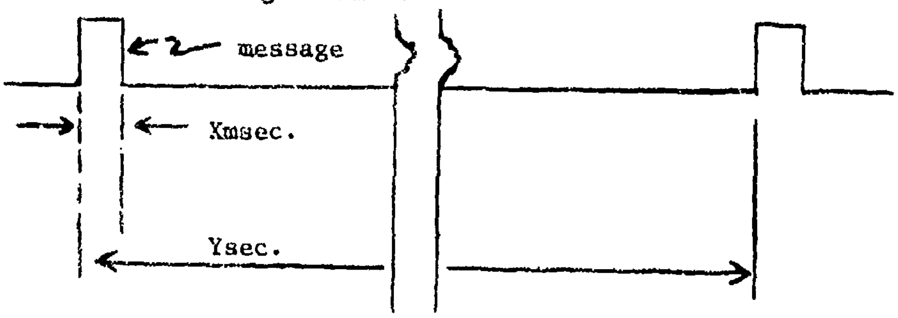


FIGURE 11-1 REMBASS MESSAGE DUTY CYCLE

In view of this low duty cycle of the message, it is reasonable to assume that the noise characteristics are approximately Gaussian during the short transmission interval. While burst type noise will no doubt be experienced at times, the probability of this type noise occurring during the short transmission period is assumed to be low enough that a simultaneous occurrence of a noise burst and a given sensor transmission will not seriously affect system performance.

6.2 Error Detection/Correction. Under the above assumptions for the characteristics of REMBASS messages, a block code is very appropriate. A block code provides a number of "check" digits for a group of data digits. The addition of check digits to the data digits either increases message duration (if bit rate is maintained), or requires an increase in bit rate if message duration is to be maintained.

The latter decreases the energy in the digit signal and requires an increase in bandwidth, both of which reduce signal-to-noise ratio (S/N). If a non-coherent communication system is assumed, then:

$$(BER)_{n\ bits} = (BER)_k^{k/n}$$

where k is the number of data digits and n is the number of digits in the message (message digits plus check digits). The BER rises exponentially, e.g. for n = 2k a BER of 10^{-4} before coding becomes 10^{-2} after coding, an increase of 100 times when the bit rate is increased to maintain message duration. Therefore, bit rate should be maintained and the added message duration accepted in the absence of other constraints. There are many types of block codes. They do no allow an arbitrary selection of n or k. Table XI-I lists the characteristics of several common error correction block codes. These are a general class of codes called BCH (Bore-Chaudhuri-Hocquengham) codes which contain other codes as sub-sets. General BCH codes are difficult to decode and therefore simpler codes would be considered for REMBASS. In particular, a Hamming code would be a probable choice if only a single error correction capability is desired.

TABLE XI-1

SOME BCH CODES

n (message digits)	k (data digits)	errors corrected
7	4	1
15	11	1
	7	2
31	26	1 Hamming
	21	2
	16	3
	11	5
63	57	1 Hamming
	51	2
	45	3
	39	4
	36	5
23	12	3 Golay

Note: In selecting a code, it is important to use an efficient code, i.e., one that provides high (k/n), for a specified number of corrected error and resultant encoding/decoding complexity.

6.3 Error Detection Only. A parity check allows rejection of all messages with an odd number of errors, but presents as correct messages those with an even number of errors as well as those messages without error.

6.4 Evaluation of Alternatives.

6.4.1 Performance.

6.4.1.1 Message Error Rate.

a) Alternative A1 - Error Detection and Correction. The assumption of a probable Gaussian noise environment in REMBASS permits the calculation, using the Bernoulli Trials Formula, of the message error rate improvement achievable through error correction. In Figure 11-2 Curve $W_{0/32}$ shows the message error rate of a 32 digit message as a function of bit error rate (BER). Curves $W_{1/32}$, $W_{2/32}$, and W3/32 show the message error rate when one, two, and three errors in the 32 digit message are corrected. Reference to these curves does not reflect the whole story. Each message must have an alerting preamble for message recognition and synchronization (identification of the first data digit). Curves F_8 and F_5 in Figure 11-2 show the failure of an eight digit and a five digit preamble under conditions of same BER, with no error correction. Note that with these preambles, the failure rate of the preamble causes message loss and therefore limits the attainment of the full improvement that comes from the correction of just one error in the message. With this kind of preamble error rate, there is no point in correcting more than one error in the remainder of the message. It behooves us to use a preamble which is less susceptible to errors. One method would be the use of a "Barker Code" for a preamble. Curves $W_{1/8}$ and $W_{2/8}$ of Figure 11-2 indicate the preamble failure rate when one and two errors are permitted. In Figure 11-3 the possible message error rate improvement from using a 7 bit Barker sequence followed by 3 blocks of a (15, 11) code (15 digits in each block, of which 11 are data digits) is shown. This 52 bit message efficiently accomodates 32 data digits. It can correct one error per block. The improvement in message error rate relative to a 32 bit uncorrected message is shown. The preamble error rate is also shown, which allows one bit error in the 7 bit Barker Code for the given preamble error rate.

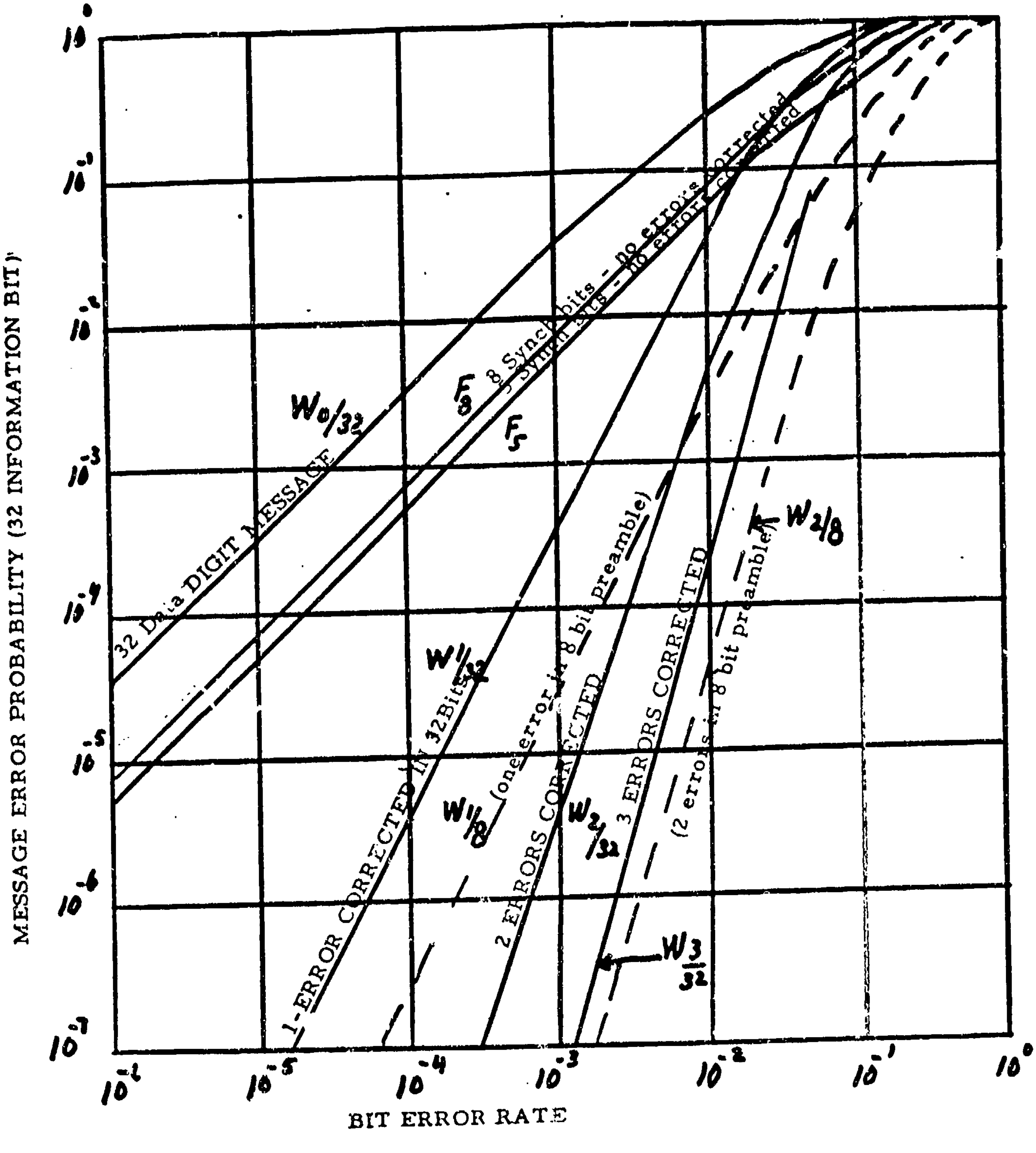


FIGURE 11-2 MESSAGE ERROR PROBABILITY vs. BIT ERROR PROBABILITY

3 Blocks of (15, 11) Hamming Code (1 error corrected)
7 Bit Barker Synch

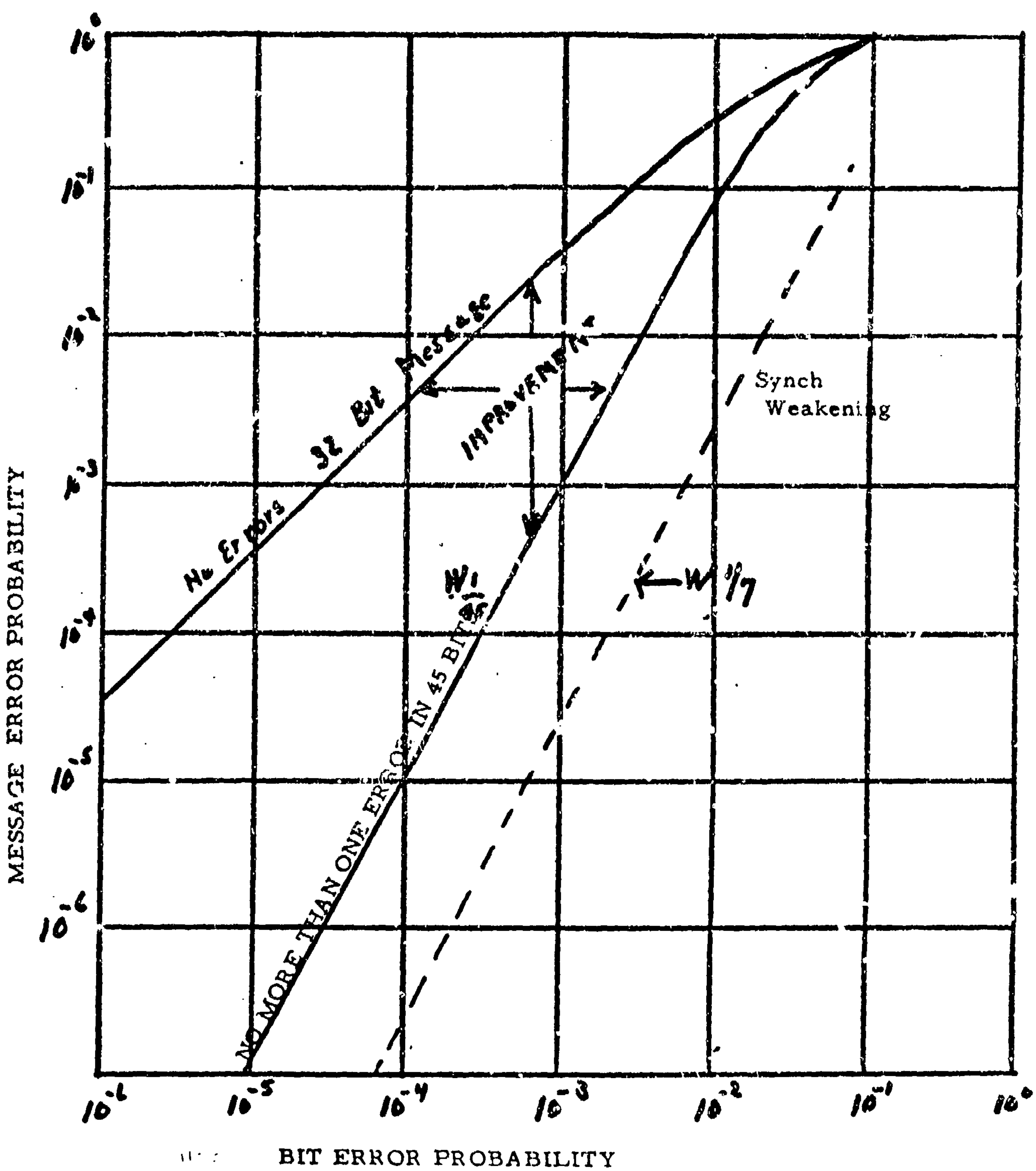


FIGURE 11-3 SINGLE ERROR CORRECTING CODE PERFORMANCE

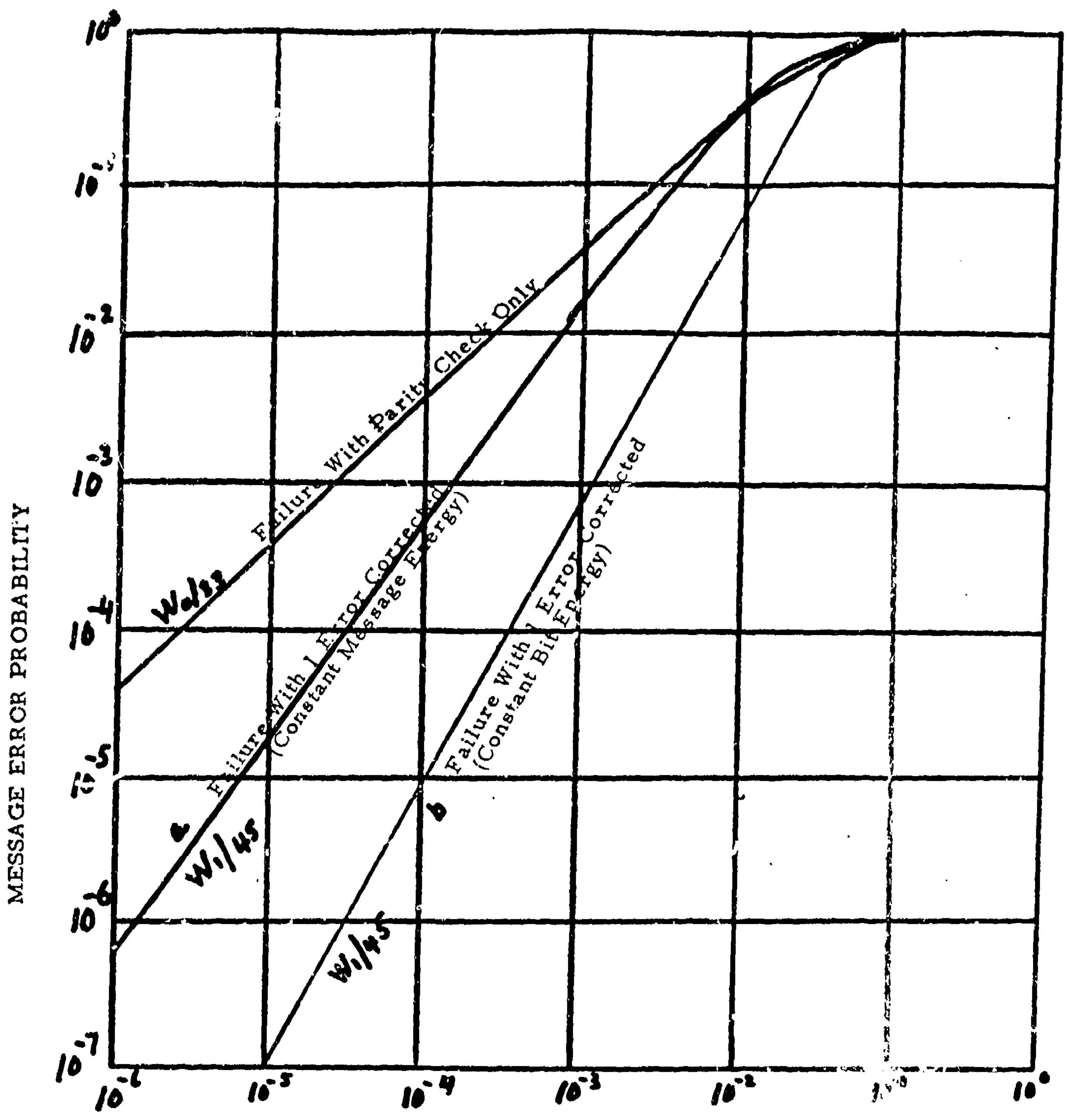
b) Alternative B1 - Error Detection Only. A simple parity check enables the differentiation of received messages into two categories: 1) those that have an odd number of errors which usually are screened out (not displayed); and 2) those that have either an even number of errors or no error and which are presented. The parity check system also rejects correct data messages in which the parity check bit is in error. Two questions are of interest in evaluating the relative performance of the simple parity check: A) What percentage of received correct data messages are not displayed (missed) in each alternative; and B) What percentage of the displayed messages are in error? The answers to these questions varies with BER. From the cumulative data digit errors (i.e., more than zero errors, more than one error, more than two errors, etc.) or correctly synched messages obtained from the Bernouilli Trials Formula for a 32 digit data message the relative standing of the alternatives are shown in Table XI-II.

TABLE XI-II

ALTERNATIVE RELATIVE STANDING

BER of 10^{-2} (a relatively high BER)	% messages displayed	% of displayed messages in error
32 data digit message	100	27.5
32 data digits + parity	76	5.2
One error corrected (3 blocks - 15, 11)	99	6.5
BER of 10^{-3}		
32 data digit message	100	3.15
32 data digits + parity	97	.05
One error corrected	99.99	10^{-4}

Parity check reduces the percentage of displayed messages with errors. In a relatively high BER situation many correct messages will not be displayed (and therefore missed), using a parity check. Figure 11-4 shown the relative improvement in message error rate between error detection (parity check) and single error correction under 2 conditions, maintaining message energy (increased bit rate) and maintaining bit rate. Errors include messages received with errors and therefore not displayed, and displayed messages which may be in error.



Error Detection: n, k = 33, 32; Preamble = 7 Total digits 40
1 Error Corrected: 3 blocks (15, 11); Preamble = 7 Total digits 52

FIGURE 11-4 COMPARISON OF CONSTANT BANDWIDTH AND CONSTANT BIT ENERGY CODE PERFORMANCE

c) Alternative C1 - No Detection/Correction. As shown in Table XI-II this alternative is inferior to any other alternative in terms of error prrformance.

6.4.1.2 Message Energy Requirements.

a) Alternative A1 - Error Detection/Correction. Message energy requirements increase directly with increased bits, assuming constant bandwidth is maintained. In order to keep message energy independent of added code bits, a higher bit error feasability must be accepted. For purposes of comparing the alternatives, a longer message is assumed and therefore, this alternative requires a greater message energy to obtain improved performance.

b) Alternative B1 - Error Detection Only. This alternative only requires adding a single bit to a message; therefore, for reasonably long messages of the REMBASS type, no appreciable increase in message energy is required.

c) Alternative C1 - No Detection/Correction. No increase in energy for messages by virtue of the definition of the alternative.

6.4.1.3 Message Self-Interference.

a) Alternative A1 - Error Detection/Correction. Increased self-interference is directly proportional to the increased message duration; therefore, this alternative is expected to result in increased message interference.

b) Alternative B1 - Error Detection Only. Due to the insignificant increase in message length due to an added parity bit, no appreciable self-interferer should result.

c) Alternative C1 - No Detection/Correction. No additional self-interference by definition.

6.4.1.4 ECM/EMI

a) Alternative A1 - Error Detection/Correction. This criterion relates to the probability of enemy detection of a message, or interference with other colocated data systems. The longer the message duration, the higher the probability of either; therefore, relative to other alternatives, this alternaiive would be ranked lowest.

b) Alternative B1 - Error Detection Only. This alternative would rank close to Alternative C1 due to the minor difference in message lengths of the two alternatives.

6.4.2 Cost.

6.4.2.1 R&D Costs.

a) Alternative A1 - Error Detection/Correction. Although the technology and circuit design is straightforward for developing this alternative, there would still be appreciable cost associated with fabricating LSI masks, etc., for producing the required circuits; therefore, the R&D costs associated with this alternative would necessarily be greater than the other alternatives.

b) Alternative B1 - Error Detection Only. This alternative requires only a single binary flip-flop plus gating; therefore, no appreciable R&D cost would be required to implement it.

c) Alternative C1 - No error Detection/Correction. No additional R&D costs required.

6.4.2.2 Acquisition Costs.

a) Alternative A1 - Error Detection/Correction. Acquisition costs are dependent to some extent upon whether error correction will be performed in the repeaters. For a single error correction system it would probably be desirable to correct the message before retransmitting it. This would increase the cost of this alternative. In any case, since each sensor must include the message encoding capability, the acquisition cost of this alternative would be significantly greater than either of the others.

b) Alternative B1 - Error Detection Only. No appreciable increase in acquisition cost should result over no error detection.

6.4.2.3 Life Cycle Support Costs. The only impact on life cycle support costs for any of the alternatives would be in the maintenance time, skills, and equipment requirements. For this criterion, Alternative B1 and C1 would rank equally, with Alternative A1 ranking somewhat lower due to the added circuit complexity which would reflect in a possible higher mean-time-to-repair.

6.5 Electronic Counter Countermeasures (ECCM) Coding. The type of ECM which are commonly used against an RF communication system are: a) broadband noise-life RF radiation; b) simultaneous transmission of burst type interference signals by an enemy when he detects a suspected transmission, without regard for what the transmission consists of; and c) "spoofing", where transmissions are recorded by the enemy and used for future transmission to simulate a real message. ECCM coding may provide a certain measure of security against either of the above types of ECM, depending upon the type of transmission technique used for the communication system.

For example, if wideband transmission is used, coding of the transmitted data may be used to simulate noise provided adequate processing gain is available in the receiver using matched filter or correlation detection. In this way the ability of the enemy to detect the transmission may be practically eliminated. If narrowband data transmission is used, the ability of the enemy to detect transmissions is good, therefore, ECCM coding would not provide security against the type: 1); and 2) ECM above. Against "spoofing", or imitative signal transmission, certain coding techniques can provide a good measure of security. Since the results of the DTS engineering analysis 1 seem to indicate that a narrowband communication system is the dominant alternative, and since a narrowband system is easily spoofed, some type of secure coding should be considered for part of the digital message. The subject of secure coding has been discussed with NSA personnel. If REMBASS desires to use a crypto code for data messages, NSA will have to be provided with an operational description (concept) for REMBASS, from which to decide whether they will agree to provide us with a classified microcircuit "Chip" (similar to that for the Air Force SEEK BUS and the Army/Marine's PLRS), which could be designed into all encoders.

TABLE XI-- III

RELATIVE RATING OF ALTERNATIVES vs. CRITERIA

	CRITERIA						
	COSTS			PERFORMANCE			
ALTERNATIVE	R & D	ACQUISITION	LIFE CYCLE SUPPORT	MESSAGE ERROR RATE	MSG. ENERGY REQUIREMENTS	MSG. SELF INTERFERENCE	ECM/EMI
A. Single Error Correction	8	7/8	8	10	7	7	7
B. Error Detection Only	10	10	10	2/7	9	9	9
C. No Error Coding	10	10	10	0	10	10	10

7.0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III, paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal maximum, and minimum values of the weighting factors used are given in Table XI-IV.

Table XI-V lists the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion. The evaluation scores in this table are accurate to two significant figures. The last line is the Evaluation Rating (ER) or weighted score for each alternative.

7.2 Secondary Ranking Techniques. The procedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section are applicable. The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Table XI-VI.

7.3 Comparison of Results-Nominal Values. From Table XI-VI , the ranking of the alternatives showed little stability throughout the performance of the four analytical techniques. Alternative B realized the first and second rank positions an equal number of times. Alternative C was first ranked twice and once each for the second and third rank positions. Alternative A realized the second rank position once and the third, three times.

TABLE XI-IV

WEIGHTING FACTORS

	NOMINAL WEIGHT		WEIGHT RANGE	
	MAJOR FACTOR	SUB-FACTOR	MINIMUM	MAXIMUM
I. COST	.4807		.3800	.5800
1. R&D		.2339		
2. ACQUISTION		.3887		
3. LIFE CYCLE SUPPORT		.3774		
II. PERFORMANCE	.5193		.4200	.6200
1. MESSAGE ERROR RATE		.3500		
2. MSG. ENERGY REQUIREMENTS		.1000		
3. MSG. SELF INTERFERENCE		.3500		
4. ECM/EMI		.2000		

TABLE XI-V

EVALUATION SCORES

CRITERIA	ALTERNATIVES A	B	C
I. COST (.4807)			
1. R&D (.2339)	8.0	10.0	10.0
2. ACQUISITION (.3887)	7.5	10.0	10.0
3. L.C. SUPPORT (.3774)	8.0	10.0	10.0
II. PERFORMANCE (.5193)			
1. MESSAGE ERROR RATE (.3500)	10.0	4.5	0
2. MSG. ENERGY REQUIREMENTS (.1000)	7.0	9.0	10.0
3. MSG. SELF INTERFERENCE (.3500)	7.0	9.0	10.0
4. ECM/EMI (.2000)	7.0	9.0	10.0
EVALUATION RATING	7.93	8.66	8.18

ALTERNATIVE KEY

A. SINGLE ERROR CORRECTION
B. ERROR DETECTION ONLY
C. NO ERROR CODING

TABLE XI-VI

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS AND DIFFERENT WEIGHTING TECHNIQUES

ALTER-	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
NATIVE	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
A	7.93	3	8.00	3	7.87	2	8.40	3
B	8.66	1	8.89	2	8.35	1	9.39	2
C	8.18	2	9.05	1	1.87	3	9.71	1

ALTERNATIVE KEY

A. SINGLE ERROR CORRECTION
B. ERROR DETECTION ONLY
C. NO ERROR CODING

8.0 SENSITIVITY ANALYSIS

The procedures and discussions presented in Section III, paragraph 8.0 apply equally to this section except that the basic data presented in this section are applicable.

8.1 Sensitivity Study Using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then three additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the three major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately. The results of the additive weighting sensitivity study are plotted in Figure 11-5. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. An examination of Figure 11-5 shows that Alternative B remained first ranked consistently. Alternative C maintained the second rank position three times and the third, twice throughout the additive weighting technique analysis. Alternative A realized the third rank position three times and the second, twice. Additionally, Alternative A showed little change in evaluation rating value throughout the analysis.

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for the three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 16 sensitivity runs were made for the analysis. Tables XI-VII and XI-VIII show the resultant evaluation ratings and the rank preference order for each of the alternatives as the indicated major criterion factor weights varied. From Tables XI-VII and XI-VIII, none of the alternatives maintained stability in rank preference order. Alternative B realized the first and second rank positions an equal number of times, directly correlating to the results obtained from the additive technique. Similarly, the results obtained for the C and A alternatives corresponded to those realized from the additive technique in that Alternative C ranked first eight times, second, twice and third, six times and Alternative A realized rank position 2, six times and 3, ten times. Table XI-IX shows the alternatives cumulative rank frequency for the 20 runs obtained from the four analysis techniques. From Table XI-IX, the trends discussed in the preceding paragraphs are evident. Alternatives B and C realized the first and second rank positions respectively, when ordered on the bases of evaluation rating mean values. While both attained the first rank position the same number of times, Alternative B attained the second rank position more times than did Alternative C. Alternative A outranked Alternative C in the second rank position but since it never attained the first rank position, it is clearly third in rank order.

The most probable rank order of the viable alternatives is as follows:

RANK	ALTERNATIVE
1	ERROR DETECTION ONLY (B)
2	NO ERROR CODING (C)
3	SINGLE ERROR CORRECTION (A)

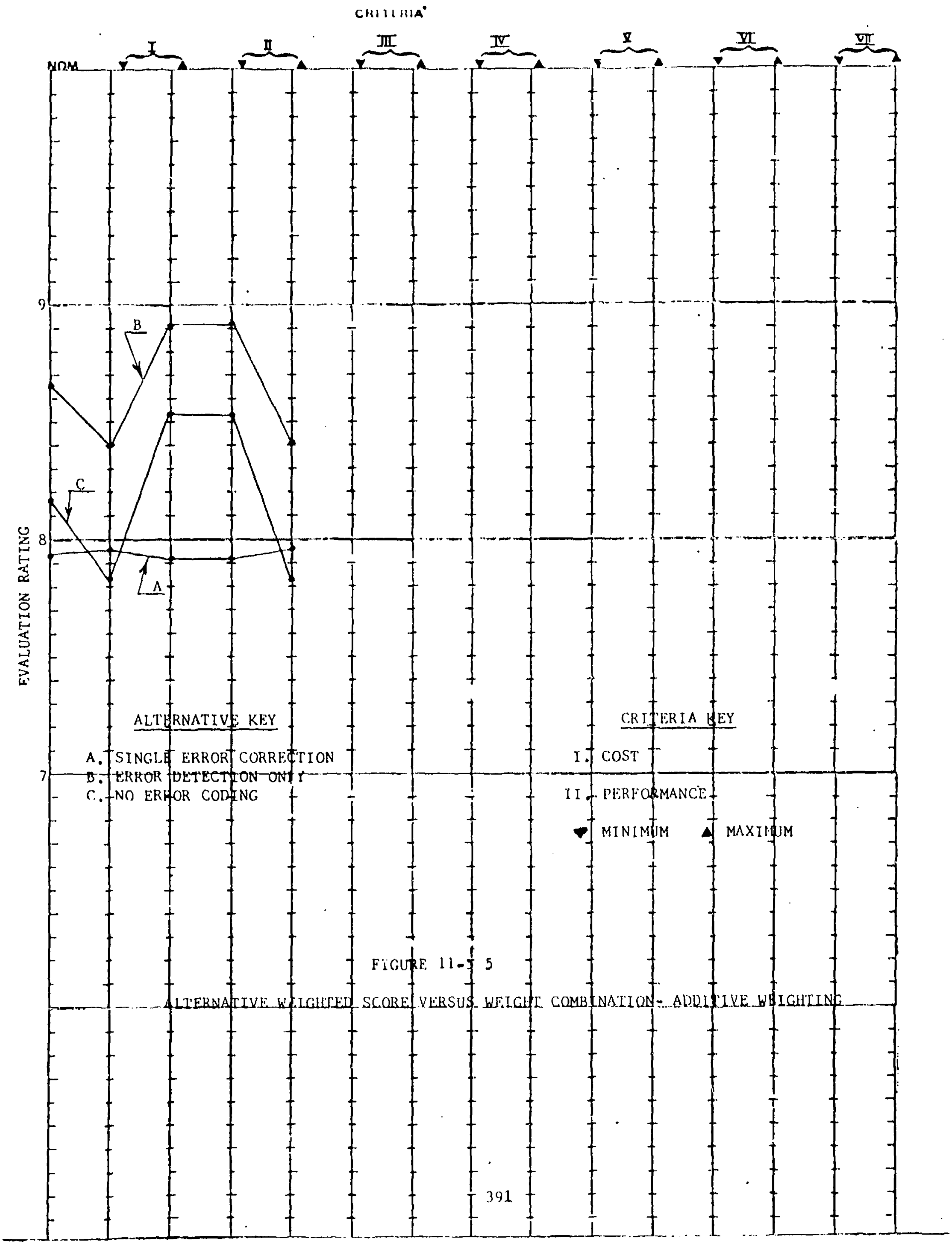


FIGURE 11-3 5

ALTERNATIVE WEIGHTED SCORE VERSUS WEIGHT COMBINATION- ADDITIVE WEIGHTING

TABLE XI-VII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING COST FACTOR

ALTER-	ADDITIVE		RMS		MULTIPLICATIVE		LOGARITHMIC	
NATIVE	RATING	RANK	RATING	RANK	RATING	RANK	RATING	RANK
MIN COST								
A	7.96	2	8.04	3	7.88	2	8.49	3
B	8.40	1	8.66	2	8.06	1	9.23	2
C	7.83	3	8.85	1	1.36	3	9.65	1
MAX COST								
A	7.91	3	7.97	3	7.86	2	8.31	3
B	8.92	1	9.12	2	8.64	1	9.53	2
C	8.53	2	9.24	1	2.58	3	9.77	1

WEIGHTS USED IN THESE RUNS

MIN COST: COST = .3800, PERF = .6200,

MAX COST: COST = .5800, PERF = .4200,

ALTERNATIVE KEY

A. SINGLE ERROR CORRECTION
B. ERROR DETECTION ONLY
C. NO ERROR CODING

TABLE XI-VIII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING PERFORMANCE FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PERF								
A	7.91	3	7.97	3	7.86	2	8.31	3
B	8.92	1	9.12	2	8.64	1	9.53	2
C	8.53	2	9.24	1	2.58	3	9.77	1
MAX PERF								
A	7.96	2	8.04	3	7.88	2	8.49	3
B	8.40	1	8.66	2	8.06	1	9.23	2
C	7.83	3	8.95	1	1.36	3	9.65	1

WEIGHTS USED IN THESE RUNS

MIN PERF: COST - .5800, PERF - .4200,

MAX PERF: COST - .3800, PERF - .6200,

ALTERNATIVE KEY

A. SINGLE ERROR CORRECTION
B. ERROR DETECTION ONLY
C. NO ERROR CODING

TABLE XI-IX

CUMULATIVE RANK FREQUENCY TABLE- ALL METHODS

ALT	MODE	MEAN	1ST	2ND	3RD
A	3	2.650	0	7	13 *
B	1	1.500	10 *	10	0
C	1	1.850	10	3	7

ALTERNATIVE KEY

A. SINGLE ERROR CORRECTION
B. ERROR DETECTION ONLY
C. NO ERROR CODING

9.0 CONCLUSIONS

The analysis indicates that a single bit parity check error detection coding for REMBASS digital data messages is preferred over single error correction coding or no coding. It is emphasized that this assumes that the DTS data messages contain no classified information. That is, reliability of data communication is the primary concern.

The DTS team does not agree with the relative weights applied to the cost subcriteria; however, this would not change the results since the rating of the two top alternatives are equal for these subcriteria.

10.0 RECOMMENDATIONS

It is recommended that a single parity check bit be incorporated with all digital data for error detection only.

SECTION XII

ENGINEERING ANALYSIS 11 - REPEATER OPERATIONAL TESTING

1.0 SUMMARY

This analysis addresses the method of repeater testing that should be employed in the REMBASS Data Transmission Subsystem (DTS). The alternatives were evaluated against a specific set of criteria; cost, performance, physical characteristics, human factors and versatility. The analysis concluded that the capability for operational testing through the command link should be included in REMBASS.

2.0 INTRODUCTION

The REMBASS system is composed of several major subsystems. Several different alternative subsystem designs may be found which provide the system operational and functional requirements of REMBASS within certain constraints. In order to determine which subsystem alternative provides the best choice, alternatives are evaluated and analyzed against common criteria and one or more possible alternatives are selected as candidates for final system components.

This report is concerned with the feasibility of having and the selection of a means for Post-Emplacement testing the operability of repeaters in REMBASS.

3.0 STATEMENT OF THE PROBLEM

After the operational deployment of a remote sensor system to provide information on enemy activity at various locations, there will be extended periods in which there will be no enemy activity reported at most if not all sensor locations because of the absence of enemy activity. Should components in the DTS particularly the repeaters fail, it would not be known if there were enemy activity in an area and a possible false sense of security would be generated. It appears that REMBASS should include means for DTS test if confidence in the system is to be maintained.

Technical means can be provided to test the DTS but it will add to system cost. It may not be necessary since enemy activity is not the only stimulus that generates sensor transmissions. Other stimuli that may provide messages on a random basis include: a) environmental events (rain, wind, thunderclaps); b) roaming anamals and; c) electronic noises. Receipt of such messages will indicate that portions, or all of the DTS are operational. Since these messages may be misinterpreted as true target messages, their minimization is a sensor design goal. Minimization of false messages however increases the period between messages, and therefore the interval during which the status of the DTS is unknown.

Whether means to generate a periodic DTS test message from a sensor is required to provide a repeater verification of operation depends on the expected sensor false alarm rate. Possible technical alternatives for testing repeaters in the DTS require analysis against pertinent criteria.

4.0 ALTERNATIVES

4.1 Automatic Self Test. In this alternative each repeater periodically tests its ability to receive messages and transmits a response message indicative of its operational status. The test does not depend on outside stimuli. One embodiment would utilize the continuously running CMOS clock of the message encoder to time an interval following which a microwatt level RF modulated signal (internally generated) would be applied momentarily to the receiver input. The receiver output level would be used to code an appropriate response message and indicate repeater operation status.

4.2 Command Test. The REMBASS Material Need (MN) includes a need for commandable sensors. In this alternative each repeater includes logic to recognize a "Test" command addressed to itself. The repeater transmits an appropriate response message. The "Test" command is generated at the Sensor Readout Unit (SRU) whenever the status of a repeater is in doubt.

4.3 Operational Test. This alternative provides an indication of repeater status from its functioning in response to sensor generated messages stimulated by enemy activity, a periodic sensor test, or non-enemy induced sensor stimulation. Failure to receive such messages at the SRU over a period of time is interpreted as the presence of a non-functioning repeater in the link.

5.0 CRITERIA

Criteria used in the comparative evaluation of alternatives of this engineering analysis are defined below. In paragraph 6.0 each alternative is evaluated against these criteria and given a comparative rating relative to the other alternatives. In arriving at a final evaluation (see paragraphs 7.0 and 8.0) each criterion is weighted in proportion to its importance as determined from MN requirements or other pertinent facts. In cases where the relative weight or relative ratings of a criterion is not considered exact, a sensitivity analysis will be performed to determine the effects of error in the weighting factor or ratings.

5.1 This criterion includes all costs of: a) research and engineering development of the test capability; b) differential end item cost involved in initial purchase and supply of each designated Army element due to the inclusion of the test capability; and c) the different costs involved to continue resupply of end items with components to provide the required test capability.

5.2 Performance.

5.2.1 Dependability. The degree to which an alternative can be relied upon to indicate repeater operability.

5.2.2 Timeliness. The relative time within which an alternative can indicate repeater inoperability after malfunction.

5.2.3 Failure Isolation. The ability of an alternative to isolate in a repeater chain or in the DTS where a failure exists.

5.2.4 Power. The additional power demands of an alternative to provide the test capability.

5.3 Size. The size or volume impact on the end item due to alternative incorporation in an end item.

5.4 Human Factors. The ease by which an alternative provides a REMBASS operator with knowledge of a repeater or DTS malfunction and its location.

5.5 Versatility. The number of applications or types of repeaters an alternative can satisfy.

6.0 EVALUATION OF THE ALTERNATIVES (see Table XII-I).

6.1 General. The function of a repeater is to receive messages from sensors or repeaters, and retransmit the message at increased power level without modification or errors. A meaningful test routine of a repeater must therefore furnish information indicating: a) the repeaters ability to receive messages; and b) its ability to forward messages. Go, No-Go type of tests would be performed on repeater functions. The status of the repeater would be coded into its response message. Test of the repeater's battery condition may be a desirable subsidiary test, as it permits an estimate of the probable remaining operating time of the repeater. Alternative 2 requires decoding of command message addresses to each repeater and execution of a test routine. Each repeater in a system is sequentially addressed, starting with the one closest to the command transmitter station. Failure of the closest repeater to respond with a status message indicates it is inoperative. This will usually "black out" responses from all repeaters further down the transmission path. This alternative may also permit determination of whether a commandable sensor is operable. A test or other command is addressed to a particular sensor. If no response message is received to this command, and a response message is received from its "servicing" repeater following a repeater test command addressed to this repeater, it may be concluded that the addressed sensor is inoperative. Non-commandable sensors would depend on proper target activations or false alarms for testing. One embodiment of alternative 3 applicable to non-commandable sensors, causes each sensor to send a periodic message indicating its operational status. If a test message is received from a non-commandable sensor serviced by the "last" repeater in a link at test intervals, the entire system is operational.

Failure to receive a "test" message from one or all sensors or repeaters in the time interval in alternatives 1 and 3 can initiate an audible or visual alarm in the SRU.

6.2 Costs.

6.2.1 R&D Costs. R&D Costs of all alternatives are similar and minimal since the designs would be straight forward using available components and circuitry.

6.2.2 Acquisition Costs.

6.2.2.1 Alternative 1 (Self Test). This alternative requires addition of costly components to repeaters.

6.2.2.2 Alternative 2 (Command Test). This alternative can be built into the logic of repeaters of the DTS at negligible cost, assuming that REMBASS utilizes commandable sensors. Since the REMBASS MN specifies the use of commandable sensors, the assumption seems valid.

6.2.2.3 Alternative 3 (External Stimulation). If a periodic test message is not necessary, this alternative does not add to system cost. If a periodic test message from sensors is required, the necessary test message encoding logic can be incorporated in the design of the encoder and provided at little added cost to each sensor.

6.2.3 Life Cycle Support Costs (see Table XII-II for summary).

6.2.3.2 Consumption. Alternative 1 has high unit cost components but these are only required in repeaters, so consumption cost is moderate. Alternative 2 can be incorporated in repeater decoder and encoder chips at negligible cost, so consumption cost is expected to be lowest of alternatives. If a periodic sensor test message is not required, no consumption costs are involved in alternative 3. However, if a periodic sensor test message is required, provision for this must be incorporated in all sensors. In view of the large sensor population consumption cost would be highest.

6.2.3.3 Integrated Logistics Support. Since additional parts would have to be provided for alternative 1 its integrated logistics support cost is greatest.

6.2.3.4 Transportation. This criterion is of little consequence in all alternatives.

6.2.3.5 Depot Maintenance. Since alternative 1 has the greater number of parts, its depot repair cost is higher than alternative 2. If no periodic sensor stimulation is required, its cost will be lowest. If alternative 3 requires means for periodic sensor stimulation, items subject to repair will be high and the alternative can have the highest repair cost.

6.3 Performance.

6.3.1 Dependability. Alternative 2 is more dependable since the test can be repeated as often as desired. Alternatives 1 and 3 are of equal dependability but less dependable than alternative 2.

6.3.2 Timeliness. Alternative 2 can provide the more timely alert of malfunction since a test command can be sent whenever desired. Alternatives 1 and 3 are likely to be equally less responsive to a repeater failure than alternative 2.

6.3.3 Failure Isolation. Alternatives 1 and 2 permit the identification of the portion of a repeater link that is functional. Failure to receive a test or command response message from repeaters beyond a particular repeater indicates one or more of the further removed repeaters (from the SRU), is not operating. Which of these further removed repeaters is not functioning, cannot be determined. In alternative 3 if sensors are clustered around only the most distant repeater, the failure of any repeater will cause loss of all sensor messages, and the faulty repeater cannot be isolated. However, if sensors are clustered around each repeater the limit of DTS operability can be determined to the same extent as in alternatives 1 and 2.

6.3.4 Power The added power requirements to provide repeater test for all alternatives is inconsequential. Among the alternatives, 3 requires power only to relay messages. Alternative 2 requires slightly more power, while alternative 1 requires the most power in relation to the other alternatives.

6.4 Size. The size impact of alternatives 2 and 3 is insignificant alternative 1 may require a separate module.

6.5 Human Factors. All alternatives can provide the SRU operator with an automatic alert if a message from a repeater is not received in a particular interval. Since alternative 2 requires overt operator action, it is slightly more prone to operator error.

6.6 Versatility. Alternatives 1 and 3 are inflexible in that the testing is dependent on predetermined routines or external factors. Alternative 2 has complete flexibility of testing at the discretion of the operator.

TABLE XII-I

RATINGS OF ALTERNATIVES vs CRITERIA

	CRITERIA									
	R & D	ACQUISITION	LIFE CYCLE SUPPORT	DEPENDABILITY	TIMELINESS	FAILURE ISOLATION	POWER REQUIREMENTS			
ALTERNATIVES	COSTS			PERFORMANCE				SIZE	HUMAN FACTORS	VERSATI-LITY
1. Automatic Self Test	10	6	7.8	8	8	10	8	7	10	8
2. Command Test	10	10	10	10	10	10	10	10	9	10
3. Operational Test	10	3	8.5	8	8	8	9	10	10	8

TABLE XII-II
RATINGS OF ALTERNATIVES VS LIFE CYCLE SUPPORT COSTS

LIFE CYCLE SUPPORT COSTS

Alternatives	Personnel	Consumption	I.L.S	Transport	Depot Maint.
1	10	7	7	10	6
2	10	10	10	10	10
3	10	10/5	10	10	0/10

7 0 RANKING OF ALTERNATIVES USING SEVERAL WEIGHTING TECHNIQUES

The procedures and discussions presented in Section III, paragraph 7.0 apply equally to this section except that the basic data presented in this section are applicable.

7.1 Basic Ranking Technique. The procedures and discussions presented in Section III, paragraph 7.1 apply equally to this section except that the basic data presented in this section are applicable. The nominal, maximum, and minimum values of the weighting factors used are given in Table XII-III.

TABLF XII-III

WEIGHTING FACTORS

CRITERION		NOMINAL WEIGHT		WEIGHT RANGE	
		MAJOR FACTOR	SUB FACTOR	MIN-IMUM	MAX-IMUM
I	COST	.2667		.2167	.3667
	1 R & D		.2500		
	2 ACQUISTION		.2875		
	3 SUPPORT		.4625		
II	PERFORMANCE	.2667		.2000	.3500
	1 DEPENDABILITY		.2833		
	2 TIMELINESS		.2833		
	3 FAILURE ISOLATION		.2833		
	4 POWER		.1500		
III	PHYSICAL	.1333		.1000	.2167
IV	HUMAN FACTORS	.1667		.1333	.3333
V	VERSATILITY	.1667		.0833	.2667

Table XII-V lists the evaluation scores for each alternative and evaluation criterion, together with the weighting factor for each evaluation criterion. The alternative scores entered for the Support, a Cost Subcriteria, are derived from five Support Subcriteria data which were provided and are tabulated below.

TABLE XII-IV

SCORES FOR SUPPORT COST SUB-CRITERIA

	PERSONNEL	CONSUMPTION	INTEGRATED LOGOSTICS SUPPORT	TRANSPORT	MAINTENANCE	SCORE
WEIGHTING	.25	.2333	.25	.0833	.1833	
ALTERNATIVE						
A	10	7	7	10	6	7.8
B	10	10	10	10	10	10.0
C	10	10/5	10	10	0/10	8.5

The Final Score values were derived by summing the products of the relative score and the subcriteria weight for each alternative. For illustrative purposes, for Alternative A, the calculations are as follows:

$$7.8 = 10\,(.25) + 7(.2333) + 7(.25) + 10(.0833) + 6(.1833)$$

The evaluation scores in this table are accurate to two significant figures. The last line is the evaluation rating or weighted score for each alternative.

TABLE XII--V

EVALUATION SCORES

CRITERION	ALTERNATIVE A	ALTERNATIVE B	ALTERNATIVE C
I COST (.2667)			
1 R & D (.2500)	10.0	10.0	10.0
2 ACQUISTION (.2875)	6.0	10.0	3.0
3 SUPPORT (.4625)	7.8	10.0	8.5
II PERFORMANCE (.2667)			
1 DEPENDABILITY (.2833)	8.0	10.0	8.0
2 TIMELINESS (.2833)	8.0	10.0	8.0
3 FAILURE ISOLATION (.2833)	10.0	10.0	8.0
4 POWER (.1500)	8.0	10.0	9.0
III PHYSICAL (.1333)	7.0	10.0	10.0
IV HUMAN FACTORS (.1667)	10.0	9.0	10.0
V VERSATILITY (.1667)	8.0	10.0	8.0
EVALUATION RATING	8.31	9.83	8.45

ALTERNATIVE KEY

A- AUTOMATIC SELF TEST
B- COMMAND TEST
C- OPERATIONAL TEST

This initial analysis results in the following preference listing of the alternatives.

RANK	ALTERNATIVE	EVALUATION RATING
1	COMMAND TEST (B)	9.83
2	OPERATIONAL TEST (C)	8.45
3	AUTOMATIC SELF TEST (A)	8.31

Since the least accurate figures in the calculation are accurate to two significant figures, the evaluation rating given here is accurate to two significant figures.

7.2 Secondary Ranking Techniques. The procedures and discussions presented in Section III, paragraph 7.2 apply equally to this section except that the basic data presented in this section are applicable. The resultant evaluation scores and their ranks, based on nominal values, derived by each of the four analytical techniques are shown in Table XII-VI.

7.3 Comparison of Results - Nominal Values. From Table XII-VI, Alternative B was clearly ranked first by a substantial ER margin. In addition, the ER value for B was consistently large and unusually stable. Alternative C ranked second by a small margin for the Additive and RMS Technique and second by a substantial margin for the Logarithmic Technique. Alternative A ranked third for three of the four analysis techniques.

TABLE XII-VI

EVALUATION RATINGS AND RANKS USING NOMINAL WEIGHTS AND DIFFERENT WEIGHTING TECHNIQUES

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
A	8.31	3	8.40	3	8.21	2	8.84	3
B	9.83	1	9.84	1	9.83	1	9.87	1
C	8.45	2	8.64	2	8.15	3	9.08	2

ALTERNATIVE KEY

A- AUTOMATIC SELF TEST
B- COMMAND TEST
C- OPERATIONAL TEST

8.0 SENSITIVITY ANALYSIS

The procedures and discussions presented in Section III, paragraph 8.0 apply equally to this section except that the basic data presented in this section are applicable.

8.1 Sensitivity Study Using the Additive Weighting Technique. First a sensitivity study was completed using the additive weighting technique. The evaluation ratings computed with nominal weighting factors and the additive technique served as the base set of values. Then 10 additional sets of evaluation ratings were calculated using maximum and minimum weighting factors for each of the 5 major evaluation criteria. When the weighting factor for one major evaluation criteria was changed to maximum or minimum, all other major criterion weighting factors were adjusted proportionately.

The results of the additive weighting sensitivity study are plotted in Figure 12-1. The weighted score or evaluation rating is plotted against the major criteria weight combination used in the calculation. The weight-combination key for Figure 12-1 is given in Figure 12-1. An examination of Figure 12-1 reveals that all three alternatives retain their rank throughout the sensitivity study, and their rank is very stable. This agrees with the results of paragraph 7.3.

8.2 General Sensitivity Study. Three additional sets of evaluation ratings were calculated for three additional weighting techniques in the same way that the additive sensitivity study was conducted. A total of 44 sensitivity runs were made for the analysis. These runs showed that preference rankings for certain sensors remained constant while others shifted within certain bands. Tables XII-VII through XII-XI show the resultant final scores and rank order of the alternatives as the indicated major criteria factor weights were varied for the four analysis techniques.

The relationship among the evaluation scores for each alternative, the nominal weighting factors for the subcriteria and for the major criteria is as shown in Table XII-IV. Table XII-III additionally includes the maximum and minimum values for the major criteria.

When the results were compared with the results obtained for RMS, Multiplicative, and Logarithmic Weighting Techniques, the results agreed with those previously reported in this document. The ER values for all criteria were generally consistent for both minimum and maximum variation in criteria weights. No change in ranking was recorded for any of the runs. Therefore, the final ranking is as follows:

RANK	ALTERNATIVE
1	COMMAND TEST (B)
2	OPERATIONAL TEST (C)
3	AUTOMATIC SELF TEST (A)

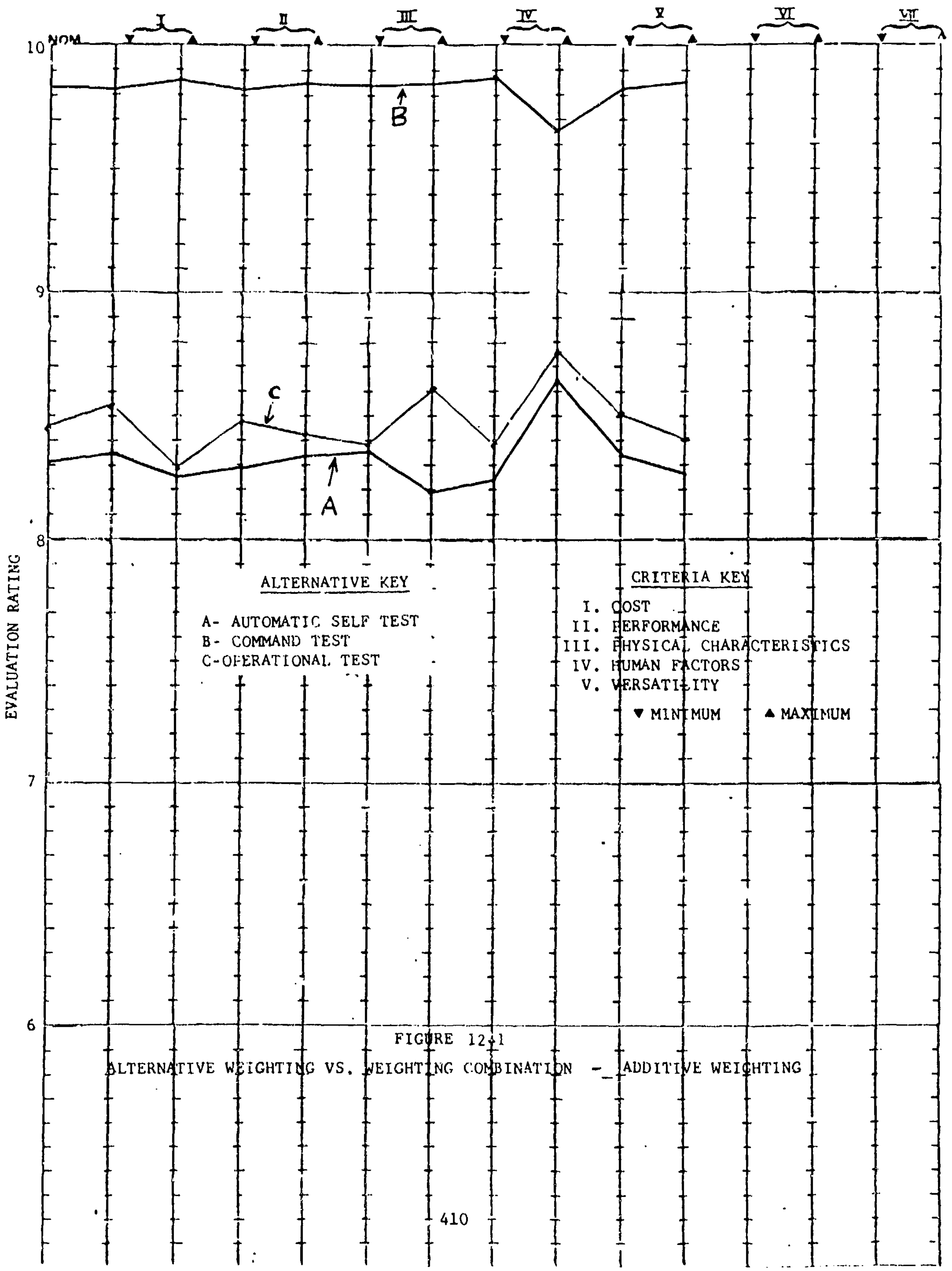


FIGURE 12.1

ALTERNATIVE WEIGHTING VS. WEIGHTING COMBINATION — ADDITIVE WEIGHTING

TABLE XII-VII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING COST FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN COST								
A	8.34	3	8.43	3	8.25	3	8.86	3
B	9.82	1	9.83	1	9.82	1	9.87	1
C	8.53	2	8.70	2	8.27	2	9.10	2
MAX COST								
A	8.25	3	8.35	3	8.14	2	8.80	3
B	9.86	1	9.86	1	9.85	1	9.89	1
C	8.29	2	8.53	2	7.92	3	9.04	2

WEIGHTS USED IN THESE RUNS

MIN COST: COST = .2167; PERF = .2849; PHYS = .1424; H F = .1781;
VERS = .1781;

MAX COST: COST = .3667; PERF = .2303; PHYS = .1151; H F = .1440;
VERS = .1440;

ALTERNATIVE KEY

A-AUTOMATIC SELF TEST
B-COMMAND TEST
C-OPERATIONAL TEST

TABLE XII-VIII

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING PERFORMANCE FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PERF								
A	8.29	3	8.38	3	8.19	2	8.83	3
B	9.82	1	9.83	1	9.81	1	9.86	1
C	8.48	2	8.68	2	8.15	3	9.14	2
MAX PERF								
A	8.34	3	8.43	3	8.25	2	8.84	3
B	9.85	1	9.86	1	9.85	1	9.89	1
C	8.42	2	8.59	2	8.15	3	9.01	2

WEIGHTS USED IN THESE RUNS

MIN PERF: COST = .2910; PERF = .2000; PHYS = .1454; H F = .1819;
VERS = .1819;

MAX PERF: COST = .2364; PERF = .3500; PHYS = .1182; H F = .1478;
VERS = .1478;

ALTERNATIVE KEY

A- AUTOMATIC SELF TEST
B- COMMAND TEST
C- OPERATIONAL TEST

TABLE XII-IX

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING PHYSICAL CHARACTERISTICS FACTOR

ALTER-NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN PHYS								
A	8.36	3	8.45	3	8.26	2	8.88	3
B	9.83	1	9.83	1	9.82	1	9.87	1
C	8.39	2	8.59	2	8.09	3	9.03	2
MAX PHYS								
A	8.18	3	8.28	3	8.09	3	8.73	3
B	9.85	1	9.86	1	9.84	1	9.89	1
C	8.60	2	8.78	2	8.31	2	9.20	2

WEIGHTS USED IN THESE RUNS

MIN PHYS: COST = .2769; PERF = .2769; PHYS = .1000; H F = .1731; VERS = .1731;

MAX PHYS: COST = .2410; PERF = .2410; PHYS = .2167; H F = .1507; VERS = .1507;

ALTERNATIVE KEY

A- AUTOMATIC SELF TEST
B- COMMAND TEST
C- OPERATIONAL TEST

TABLE XII-X

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING HUMAN FACTORS FACTOR

ALTER- NATIVE	ADDITIVE RATING	ADDITIVE RANK	RMS RATING	RMS RANK	MULTIPLICATIVE RATING	MULTIPLICATIVE RANK	LOGARITHMIC RATING	LOGARITHMIC RANK
MIN H F								
A	8.24	3	8.33	3	8.15	2	8.77	3
B	9.87	1	9.87	1	9.86	1	9.90	1
C	8.39	2	8.58	2	8.09	3	9.03	2
MAX H F								
A	8.65	3	8.75	3	8.54	2	9.16	3
B	9.67	1	9.68	1	9.66	1	9.74	1
C	8.76	2	8.93	2	8.49	3	9.32	2

WEIGHTS USED IN THESE RUNS

MIN H F : COST = .2774; PERF = .2774; PHYS = .1386; H F = .1333;
VERS = .1734;

MAX H F : COST = .2134; PERF = .2134; PHYS = .1066; H F = .3333;
VERS = .1334;

ALTERNATIVE KEY

A- AUTOMATIC SELF TEST
B- COMMAND TEST
C- OPERATIONAL TEST

TABLE XII-XI

OVERALL SCORES AND RANKS USING WEIGHTS CHANGING VERSATILITY FACTOR

ALTER-NATIVE	ADDITIVE RATING	RANK	RMS RATING	RANK	MULTIPLICATIVE RATING	RANK	LOGARITHMIC RATING	RANK
MIN VERS								
A	8.34	3	8.44	3	8.24	2	8.90	3
B	9.82	1	9.82	1	9.81	1	9.86	1
C	8.50	2	8.70	2	8.17	3	9.16	2
MAX VERS								
A	8.27	3	8.36	3	8.19	2	8.76	3
B	9.85	1	9.86	1	9.85	1	9.89	1
C	8.40	2	8.57	2	8.13	3	8.99	2

WEIGHTS USED IN THESE RUNS

MIN VERS: COST = .2934; PERF = .2934; PHYS = .1466; H F = .1834;
VERS = .0833;

MAX VERS: COST = .2347; PERF = .2347; PHYS = .1173; H F = .1467;
VERS = .2667;

ALTERNATIVE KEY

A-AUTOMATIC SELF TEST
B-COMMAND TEST
C-OPERATIONAL TEST

9.0 CONCLUSION

Command testing of operational repeaters ranked first in all four weighting techniques used in the analysis. The evaluation was predicated upon a command link being required for some sensors and therefore, did not consider a command link being included for the sole purpose of testing repeaters. If a command link is not available, the results of the analysis would have to be reviewed for the possibility of a different conclusion.

10.0 RECOMMENDATION

It is recommended that repeaters include the capability for some degree of operational testing via the sensor command link.

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